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A preliminary evaluation of biomass production and conversion technologies, and their associated environmental consequences. Five categories of biomass production were considered in detail. Thermochemical and biochemical technology were considered for conversion processes. Regionalized scenarios were prepared utilizing commercial scale plants processing appropriate regionalized feedstock. Most processes use heterogeneous solid waste as a feed stock which are believed to pose more severe control requirements for emissions and effluents than other biomass feedstocks. The environmental and socio-economic effects of locating large conversion plants in rural environments need to be studied.

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by

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

A preliminary assessment of biomass conversion to synthetic fuels has been made. This study was conducted to provide a preliminary evaluation of biomass production and conversion technologies, and their associated environmental consequences. The magnitude of the U.S. biomass resources is reviewed relative to environmental aspects of this potential source of energy. The research users will find the data base of this report an adequate starting point for further investigations into biomass utilization. It is indicated that biomass has the potential for making significant contributions to energy needs on a regionalized basis. Further information on biomass energy resources can be obtained from the IERL-Cincinnati Fuels Technology Branch.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

ABSTRACT

This study was conducted to provide a preliminary evaluation of biomass production and conversion technologies, and their associated environmental consequences. Biomass, as used in this study, refers to materials which are either directly or indirectly the result of plant cultivation. Since a substantial portion of the organic fraction of urban and industrial wastes are the "indirect" result of plant growth (that is, plant materials, especially fibers which have already been utilized in some fashion), they are considered biomass as well.

Five categories of biomass production were considered in detail; agricultural and forestry wastes, aquaculture (aquatic plant species which may be cultivated for energy production), silviculture (intense cultivation of tree species), energy crops (special crops adaptable to intense cultivation for the production of energy), and urban and industrial wastes. It was found that agricultural and forestry wastes, and urban and industrial wastes are the two categories with the nearest term potential for significant contribution to energy production in localized situations. The remaining categories represent potentially high yield biomass sources, in which varying degrees of technological innovation will be required for full development.

The conversion processes which were considered were classified as thermochemical and biochemical technology. Primary thermochemical processes which were reviewed in detail were direct conversion (including combustion), pyrolysis, and acid hydrolysis. Less developed technologies, in particular, hydrogenation and naval stores processes, were also briefly analyzed. Primary biochemical processes considered in detail included anaerobic digestion and enzymatic hydrolysis. Secondary processes (that is, processes which convert products from primary processes to useful fuels), were also evaluated and included methanol and other Fisher-Tropsch-type products from synthesis gas, ethanol production from sugar solutions, and several minor process systems.

Six regionalized scenarios (brief studies of commercial scale plants processing appropriate regionalized feedstock) were prepared as part of this work. A seventh scenario, directed at a mobile facility was also prepared.

Most processes under development use heterogeneous solid waste as a feedstock. The emission and effluents from processes when operated on solid waste are believed to pose more severe control requirements than operating the same processes on other biomass feedstock. The environmental and socioeconomic effects of locating large conversion plants in rural environments need to be studied.

This report was submitted in fulfillment of Contract No. EPA 68-02-1323 by Battelle Columbus Laboratories under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period February 12, 1976 to September 21, 1976.

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SECTION 1

TECHNICAL SUMMARY

INTRODUCTION

The diverse nature of this study, requiring data from several different disciplines, suggests the need for a technology-directed summary which is more definitive than that which is usually provided in an executive summary. This section is directed toward that need.

Sections 5, 6, and 7 are summarized in discrete sections. These are followed by a synthesis of this data to produce an evaluation of the energy potential of biomass and conversion technology. This estimate is supplemented by discussions of other relevant factors in an attempt to place biomass conversion in its proper perspective.

BIOMASS SOURCES

Approximately 50 million metric tons (55 million tons) of forest residue, on a moisture- and ash-free basis, were produced in 1971. This residue was generated predominantly in the Pacific and the southern regions. There are also other high density pockets throughout the United States. Typical dry-basis heating values for those residues range from 4450-5200 kcal/kg (8000-9400 Btu/lb). Primary technological problems to be overcome in utilizing these wastes are related to development of efficient systems and equipment to collect residue materials. Once efficient systems have been developed, it is likely that the value placed on these materials by building product industries will represent strong competition with its use for fuel.

Approximately 180 million metric tons (200 million tons) of animal manure were produced in 1971. Beef manure production was more than an order of magnitude larger than the next largest source (swine). Cattle manure is produced in two distinguishably different agricultural systems: feedlot and dairy operation. Cattle concentrations on feedlots are high, with the tendency towards the largest sizes (e.g., greater than 8000 head) becoming more pronounced. Fresh manure has a moisture content of approximately 85 percent and a dry heating value of 3450 kcal/kg (6200 Btu/lb). Most feedlot operations are in the West and Southwest. Dairy operations are concentrated in the upper Midwest. Manure from feedlots tends to be drier than that from dairy operations.

While the logistics of collection does not appear to be a technological problem in most situations (50-80 percent of all farm animals are confined), effective use of unconverted residual from likely conversion systems (anaerobic digestion system, for example) will require attention.

Crop residues are the single largest current source of biomass feedstock available for conversion to fuel. Approximately 350 million metric tons (390 million tons) on an ash- and moisture-free basis, were produced in 1971. The residues from corn, soybeans, wheat, grain sorghum, sugar cane, and sugar beet production, in that order, are the largest sources. Crop residues are concentrated in the Midwest and South. Moisture contents range from 50 to 85 percent when freshly cut but fall to 9 to 15 percent when allowed to sun-dry in the field. A typical heating value for most grain crops is 3600 kcal/kg (6500 Btu/lb); dried bagasse may reach 4400 kcal/kg (8000 Btu/lb), primarily because of its higher cellulose content. Exploitation of crop residues will require development of equipment which simultaneously harvests both crop and residue. A major constraint to utilizing these biomass sources is their seasonality.

Kelp, freshwater algae, water hyacinths, and marsh grasses are classified in the aquaculture biomass category. Giant kelp, the most discussed aquatic biomass feedstock, is limited in its natural habitat to the lower Pacific coast. Various freshwater algae are indigenous to all regions. Water hyacinths occur primarily in the South and are a freshwater species. The northern extreme of their range is limited by their susceptibility to frost. Marsh grasses are also widespread. The current harvested productivity of marsh grasses is meaningless, since they are not presently cultivated on a large scale.

Kelp can be produced, in suitable locations, with yields as high as 170 metric tons per hectare per year (75 tons/acre/year) (dry basis). However, approximately 45 percent of the dry materials are ash, predominantly salts. When harvested, kelp has a moisture content of about 88 percent.

Water hyacinths yield approximately 25 metric tons per hectare per year, dry basis, as an annual average. The fresh moisture content is reported as 94 percent.

Because of the intrinsic value in their natural habitat and their limited range, marsh grasses are not considered a significant potential source of biomass feedstock.

No data on heat content of aquaculture materials were found. However, on a dry basis, it is conservatively estimated to be on the order of 3300 kcal/kg (6000 Btu/lb), except possibly for kelp which might have a lower value because of its high ash content.

Development of kelp as a significant biomass source will require development of a complete cultivation technology. Harvesting might be accomplished by techniques presently used on a limited scale in the commercial kelp recovery industry. However, high value chemicals are recovered in these operations. Water hyacinths should be more easily cultivated and harvested. However, their limited range represents a major constraint.

Sugar cane and sugar beets were the energy crops considered in this study. The major states where sugar cane is presently cultivated include: Florida, Louisiana, Texas, and Hawaii. The states with the largest current production of sugar beets are California, Minnesota, Idaho, Colorado, and North Dakota. Approximately 290,000 hectares (740,000 acres) of sugar cane and 600,000 hectares (1,500,000 acres) of sugar beets are in cultivation; however, development of these species for biomass conversion would require substantial increases in these acreages as well as development of new varieties. Yields for sugar cane are estimated to be from 30 to 35 metric ton per hectare (13-16 ton/acre), dry basis, for current varieties, using conventional management techniques; sugar beet yields are estimated to be 10 metric tons per acre per year, dry basis. Fresh moisture content for sugar cane is about 70 percent; for sugar beets, approximately 85 percent. As noted earlier, the expected heating value for sugar cane is 4400 kcal/kg (8000 Btu/lb); a value for sugar beets was not located.

In order for sugar cane to become a significant biomass source, the area under cultivation must be extended. Likewise, new higher-total-yield varieties and more productive techniques need to be developed. Exploitation of sugar beets will require control of Nematode infestation.

Hardwood species (the generic rather than common term) are the most likely source of silviculture for energy production. Poplars and cottonwoods are the species with widest distribution. Although optimum annualized growth rate for a single species will be regionalized, each region where silviculture might reasonably be practical has species which can be adapted. Alders, which have the ability to fix nitrogen, might be particularly good species for combined energy production/reclamation activities. Yields between 2-20 metric tons per hectare per year (0.9-9 tons/acre/year), dry basis, are common for trees.

The moisture content of wood is typically 40-50 percent. Heating values between 4500-5000 kcal/kg (8100-9000 Btu/lb), including all tree parts, are common.

Cultivation and management of forests is, of course, well established. However, their use for energy conversion will require significant innovation. In particular, the practice of coppicing (e.g., forcing growth from stumps), multiple harvesting of each plant, and development of a silage-type harvester will probably be required.

As was noted earlier, strong competition for feedstock from existing wood-based industries is anticipated.

Urban and industrial wastes are produced throughout the country and, obviously, concentrated in urban centers. Approximately 270 million metric tons per year (300 million tons per year) wet basis were produced in 1973.

Approximately 66 million metric tons per year (73 million tons per year), dry basis, are "organic" and could be converted to energy. These organics typically have heating values on the order of 7000 Btu/lb on a moisture- and ash-free basis.

Collection of these residues presently is accomplished by integrated, highly complex systems of private and public organizations. However, these wastes are the most concentrated large source of biomass and, likewise, the most readily utilizable for energy production.

Major problems to be overcome relate to institutional, health, and environmental considerations.

CONVERSION PROCESSES

There exist established techniques in wood processing, food processing, pulp and paper and urban waste industries for preparing diverse biomass materials to suitable conditions of size, organic concentration, and moisture content. Details are contained in the body of this report.

Direct conversion of biomass to steam and/or electricity is the most highly developed conversion technology. Experience using wood, bagasse, and urban waste can be cited. Thermal efficiencies range from 55 to 80 percent. Equipment and process design will be a strong function of feedstock characteristics and preparation. A major limitation is the storability of these energy crops utilizing existing technology.

Pyrolysis can produce intermediate to high heating value gas streams, liquids, and chars. While a great many systems have been proposed, only 10-12 are under active development, including a mobile processing facility. Feedstocks have included municipal/industrial solid waste, agricultural and forestry wastes (wood, crop residue, livestock manure), and energy crops. Two systems have reached near-commercial levels of development. Vertical and horizontal shaft, rotary kiln, and fluidized-bed reactors have been utilized. Direct and indirect heating methods exist. The major variables affecting product yields and compositions are temperature, residence time, and feed conditions. Moisture content is a particularly important feed condition. Thermal efficiencies in the range of 50-75 percent are common.

Acid hydrolysis of cellulose (wood) to produce sugar solution for fermentation was practiced commercially before World War II. The advent of cheap petroleum brought about the demise of commercial production. Dilute and concentrated acid processes were commercialized. All previous practice was in the batch mode. In even the most advanced technology of the earlier time, 2 hours residence time was required. Besides long residence times, useless by-product formation tended to be a problem. Recently, renewed interest in the process has arisen. At a small laboratory scale, residence times on the order of 20 seconds and sugar yields on the order of 53 percent have been achieved.

Two hydrogenation technologies are under development: one produces a liquid while the other makes an intermediate grade (4500 kcal/cubic meter) gas. Close similarities to fossil fuel (especially coal) conversion processes are evident. Integrated pilot-scale demonstrations and, ultimately, modular-size demonstrations will be required before more than a tentative assessment of the value of the technologies can be made.

The naval stores industry dates to the early 1600's but has been in steady decline since the turn of the century. Many of the products produced are saturated and unsaturated hydrocarbons (e.g., terpenes). Renewal of the industry has an aesthetic appeal, because its processes yield long-chained hydrocarbons directly. However, evaluation of this potential will require an effort beyond that expended in this study.

Anaerobic digestion, as a technology, is over 100 years old and began as a sewage treatment practice. Extention to municipal solid waste has begun during the past 10 years. Two process configurations, high rate, single-stage and two-stage fermentations, have received attention. Two optimum process temperatures, mesophilic (~35 C) and thermophilic (~55 C) are utilized.

Calculations of thermal efficiencies based on published material balances yield about 50 percent.

An anaerobic digestion demonstration plant using municipal solid waste is presently under development and is being supported by ERDA. Two plants based on animal manure have also been proposed and are believed to be under development.

Enzymatic hydrolysis to produce sugar solution has been under development for about 15 years. The technology, which operates at modest process condition and without the by-product formation present in acid hydrolysis system, is still at an early stage of development. Long residence times appear to be the major stumbling block.

Biochemical production of hydrogen is still poorly developed; its commercial potential is unknown.

A number of secondary conversion processes, i.e., processes which convert the products from other technologies to useful fuels (ethanol from sugar solutions, methanol from pyrolysis gas), have been considered. Most of these processes are commercially available. Examples include: methanol, ammonia, hydrocarbon, and higher alcohol production from synthesis gas and ethanol fermentation. In most of these cases, the major effort required is adapting them to developing technologies. In a few cases, notably C_2-C_5 production from synthesis gas and gasoline from methanol, basic process development and/or demonstration will be required.

Product storage and distribution will, by and large, require use of existing technology. However, since many of these products will be used in situations where their intrinsic dangers are not well understood (for example, in municipal departments and rural, agricultural environments), a sense of caution reinforced with intensive training will be required. This is particularly true of methanol, where distribution in existing consumer fuel delivery system, could pose significant danger to the public at large.

Six regionalized scenarios, involving production and conversion technologies, were developed as part of these studies. The purpose was to demonstrate a recommended analysis technique and propose initial direction, rather than definitely assess technological and environmental effects which would occur. It is possible, however, to begin to appreciate the scale of development required for implementation of these technologies and to preliminarily suggest approximate levels of streams requiring disposition. The interested reader is referred to Sections 6 and 7 for details.

ENVIRONMENTAL ASSESSMENT

A preliminary assessment of the environmental consequences of biomass production and conversion was prepared.

Development of forestry residue and/or silviculture as a biomass source is expected to raise environmental issues in the areas of land use, physical and chemical alteration of the environment, and ecological effects. Land use considerations are expected to focus on other valuable uses of the land (and its tree crop) as well as the more aesthetic aspects related to removing logging wastes. Physical and chemical alterations, in particular, those associated with increased erosion and nutrient release, are expected to be critical questions. Assuming erosion and nutrient release effects occur in at least modest amounts, the secondary effects on the aquatic population and diversity will have to be considered. The small amount of data which were accumulated are reviewed in the text.

The environmental assessment for agricultural crop residues and energy crops were developed as a single unit. Qualitatively, these effects are similar to those noted above. However, questions relating to productivity and nutrient release are of overwhelming importance for these biomass sources, as substantial reduction of soil productivity could adversely affect human and/or animal food production. A thorough analysis of these effects will be necessary.

The concept of recovering energy from animal manures and returning the residue (at least from anaerobic digestion processes) to the land, appears to have generally favorable environmental effects. The major concern will be application rate and assurance of sites for use of the residue. When actual systems are installed, close monitoring of surface and subsurface waters will be advisable to assure these systems are not adversely affected.

The environmental effects of large-scale aquaculture are speculative. At near shore sites, favorable effects related to increasing species diversity are accrued. Unfavorable effects relate to sea-floor coverage by detritus and introduction of species into new regions. Deep-ocean farming appears to circumvent most objections. However, the state of development is so early that even preliminary analysis will require a more substantial effort.

Harvesting of marsh plants does not appear to be acceptable on a large scale, from an environmental point of view.

The environmental effect of municipal waste "production" was given only nominal consideration due to the multiplicity of studies of this waste. Generally favorable effects are believed to accrue from properly managed systems. Heavy metal concentration and disposition is the major area for concern.

The process stream requiring closest monitoring in direct conversion systems will be the stack. Particulate will be important, as may be gas-phase metallic fume and organic "hydrocarbon" concentrations, especially in process systems where municipal solid waste is burned. Proper ash disposal will also be required. For biomass originating from crops, returning the nutrient to the soils from which they were removed may be possible. Ashes emanating from direct conversion systems based on municipal solid waste and marine crops (e.g., kelp) may require special disposition.

Air emissions from pyrolysis processes will be low compared with direct conversion systems because the products are generally combusted off-site. However, the sum total will not be grossly different. Combustion conditions in pyrolysis systems are more uniform and product gas clean-up requirements are not as extensive as in direct conversion systems.

The pyrolytic oils which are prepared will likely produce higher NO_x emissions than comparable hydrocarbon analogs, because of the inherently higher nitrogen content of the feedstock. However, sulfur emissions will be lower on a comparable basis. Waste water parameters from pyrolysis conversion systems are expected to be well within conventional sewage treatment practice.

Because of its origin in sewage treatment technology, much is known about the qualitative aspects of waste streams leaving anaerobic digestion systems. Disposition of the digester broth (fermentation media) will be of prime concern. These concerns will be magnified during upset conditions if the digester contents must be released. With most biomass feedstocks, disposal to the soil will be acceptable if properly managed.

If the product gas is upgraded to pipeline quality, emissions of hydrogen sulfide from the acid gas removal system are expected. If these must be controlled, the technology should be within the range of conventional practice.

Emissions and effluent stream characteristics from other conversion technologies were not developed as part of this study.

Crude quantification of the several process systems at commercial production scale are given at the end of Section 7. These should be considered highly tentative and in need of expansion. In particular, the environmental effects associated with production should be added and the process emissions greatly strengthened.

ERDA currently provides the major thrust in biomass conversion technology development. This effort was preceded by that at NSF. Besides EPA, other agencies with identified missions in this technology include NSF, USDA, NASA, and HUD.

ENERGY POTENTIAL OF BIOMASS

Having discussed in detail the availability of biomass sources, conversion systems for these sources, and their environmental implication, it is appropriate to provide an estimate of the significance of these technologies in relation to the total energy supply picture. Such estimates always should be treated with a healthy skepticism but must be made in order to provide insight to the decision-maker on relative support work appropriate for these technologies, given the limited resources available. In preparing the estimates for biomass, the following strategy has been adopted.

A conservative estimate, on a relatively current basis, was made for the total quantity of feedstock available from each source category. Using a typical heating value for each category, the gross amount of energy available in the category was then calculated. This approximates the total energy pool currently available and is probably the data in the analysis with the highest confidence factor. Next, an estimate was made of the amount that might be collected for conversion. The assumption here is that a concentrated but not all-out effort is made to assemble the various sources. These values should be treated as highly uncertain and represent little more than educated guesses. The product of these estimates and those of the energy pool provides an estimate of energy available at the biomass plant sites for conversion to synthetic fuels. Next, a typical thermal conversion efficiency is estimated for each source category, with the value chosen primarily based on whether thermochemical or biochemical processes would be the predominant choice for conversion. The confidence level on these data is higher than that for availability but still not beyond one significant figure. The product of these numbers is the net energy that might be available for consumption. These results are shown in Table 1.

To allow other investigators to adjust the basis as is necessary for their use, the following supplemental data taken from the text is provided. The estimates of municipal and industrial organic waste available were derived from Smith(1). The data were published in 1976 but represent inventories for the year 1973. The categories used included the paper, wood, food, and yard components of solid waste.

Agricultural and forest wastes were used directly from Anderson(2). The data were published in 1972 and were for the year 1971.

Silviculture was estimated in the following manner. EPA(3) has estimated that 4.4 million acres of strip-mined land are presently in need of reclamation. This is increasing at approximately 200,000 acres per year, and about 50 percent of the total is associated with coal mining. It was assumed that about one-half the 4.4 million acres might be available for silviculture use and that a sustained annual yield of approximately 3 tons/acre/year could be reasonably expected on these low productivity lands. Obviously, there are other marginal lands which might be used for silviculture. However, their availability on a long-term basis is questionable.

The basis for energy crop estimates is current production figures for sugar cane and sugar beets. There are presently about 291,000 hectares (740,000 acres) of sugar cane under cultivation in the United States. There are land areas available for expansion, and different species might be used to increase total biomass yields. However, there are also other demands for the product, so that only the yield from current cultivation was used, and a net value of 14 dry tons per acre was estimated. It should be noted that the most likely energy use for these crops may be in the context of current production facilities, e.g., in boiler. Sugar beet production was treated similarly but represented a much smaller quantity. Marsh grasses were assumed to be insignificant.

Aquaculture's contribution was estimated based on the 100,000-acre kelp demonstration plant being utilized. Since this technology is in an early stage of development, it is believed to represent the most significant source of error in the estimation.

The data contained in Table 1 indicate that an estimated gross total of 10 Quads of energy might be available from the biomass sources considered, that possibly 4 Quads might be available for conversion, and that slightly less than 3 Quads might be available in produced fuels. Since these estimates are based on current availability, they are best compared to the present energy demand which is on the order of 70 Quads. These values would then represent approximately 15 percent, 6 percent, and 4 percent, respectively, of the current energy demand. This is not completely valid, of course, because the energy expended by the processes and equipment to collect and convert this energy are not available. However, the estimated gross energy pool is likely to generally follow the population (and total energy demand growth) during the coming development years, and the gross pool is the basis for subsequent calculations as have been described. Consequently, it is estimated that, given the multitudinous counter-balancing effects which will occur between now and the turn of the century, approximately 4 percent of the energy demand in the year 2000 might be met by biomass sources. If the total demand is on the order of 150 Quads as some have estimated, this might amount to 6 Quads. Furthermore, if significant inroads are made in energy conservation and solar heating and cooling technologies, it might be a considerably more significant source of storable, transportable fuels.

The calculated energy potential can be compared with the ERDA objective for Fuels and Biomass(13), keeping in mind that the ERDA estimate does not include solid waste. The calculations described above are certainly substantially less rigorous than those prepared by ERDA and were done completely independently. The good agreement (ERDA's objective was 2-5 Quads before the year 2000) is probably fortuitous. The relative magnitudes developed in this estimate, however, should be approximately correct.

While these calculations are informative, to base value judgments solely on their relative magnitude is to miss much of the significance of the biomass effort. To put the problem in perspective, consider the magnitude of a Quad of energy, namely 10^{15} Btu. An order-of-magnitude estimate of the energy utilization of a modest-size city (Columbus, Ohio) was prepared to provide this insight. The local newspaper(14) prepares a weekly accounting of the natural gas and electricity usage for Franklin County, which approximately represents the Columbus area and includes a population on the order of 1 million people. The electricity demand was converted to fuel by using a heating rate of 10,000 Btu/kwh, a typical value for a relatively modern power boiler. This was supplemented by data from the Ohio Public Utilities Commission(15) which provided estimates of the liquid fuel consumption for Franklin County (approximately 12.5 million barrels per year). These data allowed the estimate contained in Table 2 to be prepared.

It is clear from these calculations that several plants producing on the order of 0.1 Quads would have a significant impact on the energy consumption of a city the size of Columbus, a fairly large city by midwestern standards. Using the data developed in Table 1 for crop wastes, this would require on the order of 40,000 metric tons/day, wet basis, or probably 4 large plants, to produce 20 percent of Columbus' current energy demand.

This analysis suggests another characteristic of biomass utilization which is important. By far, the largest source of biomass available is agricultural and forestry wastes (see Table 1). These residues predominantly occur in the nation's broad midlands. This area also is characterized by a number of medium- to large-sized cities (50,000 to 1,000,000) and a tremendous number of smaller communities. These smaller communities characteristically service agricultural areas and are often near terminal points on energy distribution systems. They are difficult and expensive to service, both in monetary and energy terms. Consequently, it would seem to make good sense to use the local resources (energy crops and agricultural and forestry residues) to provide for local energy needs.

In order to visualize a third consideration, attention must be refocused on Table 1. The last category (aquaculture), on the basis of current projections, represents a minimal impact. Yet, if each of the other categories are considered in relation to expanding the energy supply available, an upper limit is quickly reached. For example, even with much higher recovery rates and greater than expected population growth, it is hard to visualize more than 1-2 quads available from solid waste. Likewise, assuming new total biomass crop species and development of organized efficient collection system, to expect more than about 10 quads from

TABLE 1. ENERGY SUPPLY ESTIMATE FOR BIOMASS (1973)

Feedstock	Typical Component	Estimated Gross Availability Million Metric Tons/Year (moisture and ash-free)	Estimated Heating Value Btu/lb (MAF)	Potential Energy Available (quads)	Percent Assumed Recoverable
Urban and Industrial Wastes	Municipal Solid	66(4)	7000(5)*	1.0	40
Agricultural and Forest Wastes	Forest and Crop Residue (corn silage)	445(2)*	6500(6)*	6.4	30
	Manures (cattle)	200(2)*	6300(7,8,9)*	2.8	60
Silviculture	Alder	8	8700(10)*	0.2	90
Energy Crop	Sugar Cane	15	8000(11,12)*	0.3	90
Aquaculture	Kelp	2	6000**	< 0.1	90

TABLE 1. (Continued)

Feedstock	Net Energy Recoverable Before Conversion (quads)	Typical Thermal Conversion Efficiency	Net Erergy Recoverable
Urban and Industrial Wastes	0.4	0.7	0.3
Agricultural and Forest Wastes	1.9	0.8	1.5
	1.7	0.4	0.7
Silviculture	0.2	0.7	0.1
Energy Crop	0.3	0.7	0.2
Aquaculture	<0.1	0.4	<0.1

* Numbers in raised parentheses denote references which are given on page 13.

** Assumption.

TABLE 2. ESTIMATE OF ANNUAL ENERGY USAGE FOR THE CITY OF COLUMBUS, OHIO

Category	Energy Use, Quad	Percentage of Total
Natural Gas	0.37	72
Electricity	0.09	18
Liquid Fuel(a)	0.04	8
Total	0.50	100

(a)Includes gasoline, distillate, residual, kerosene, and liquefied petroleum gases.

agricultural production of all types would be unrealistic, considering other nonfuel demands for these materials which are likely. The single exception to this agreement is aquaculture. The potential is staggering, far beyond the estimates provided in Table 1. The problems that must be resolved to exploit these resources are multitudinous, very difficult, and will likely require decades of concentrated effort. Yet the fact remains that, given a significant commitment, the problems can be resolved, and it is the only biomass source without a clear upper bound on its availability.

Finally, various experts have estimated the total reserves of fossil fuel. Some have suggested that several hundred years are available when coal is included. A quite interesting case is made by Huebler(16) , who has projected, based on world energy demands since 1850, that if the history of worldwide energy growth rate is maintained, all fossil fuel reserves will be depleted before the middle of the next century. Given the energy demand likely from developing countries, such an assumption does not appear overly conservative. While the relative merits of the various energy demand estimates can be argued unendingly, two facts remain. The first is that, within the foreseeable future, fossil fuel reserves will be exhausted. Secondly, as they are depleted, they will become more and more dear for a variety of uses. The conclusion is inescapable: biomass conversion will eventually be implemented. The only question is when. While direct solar and fusion application may supply large quantities of future energy needs, it is unlikely that the need for gaseous and liquid fuels will disappear completely or even decrease significantly from their current levels. It seems that the wiser choice is to begin now while we have a substantial lead on the problem and can devise solutions which minimize environmental and sociological effects rather than delay to a time when fossil energy reserves more closely approach exhaustion.

REFERENCES TO SECTION 1

1. Smith, F. A. 1976. Quantity and Composition of Post-Consumer Solid Waste: Material Flow Estimates for 1973 and Baseline Future Projects. Waste Age 7:2, 6-10.

2. Anderson, L. L. Energy Potential from Organic Wastes: A Review of the Quantities and Sources. U.S. Dept. of Interior, Bureau of Mines Information Circular 8549, Washington, D.C. 16 pages. 1972.

3. EPA, 1974. Surface Mining of Coal, EPA Report No. 670/2-74-093.

4. Klass, D. L. 1976. Wastes and Biomass as Energy Resources: An Overview. pp. 21-58. In Symposium Papers Clean Fuels. Orlando, Florida. January 27-30, 1976. Institute of Gas Technology.

5. Jackson, Frederick. Energy from Solid Waste. Noyes Data Corporation, Park Ridge, New Jersey, 1974, Chapter 1.

6. Szego, G. C. and C. C. Kemp. Energy Plantations. Chapter 3 in New Resources from the Sun. Proceedings of the 34th Annual Conference of the Chemurgic Council, Washington, D.C., November 1-2, 1973. Various paging.

7. Wells, D. M., G. A. Whetstone, and R. M. Sweazy. Manure, How it Works. Paper Presented at the American National Cattlemen's Association/Environmental Protection Agency Action Conference, August 28-29, 1973, Denver, Colorado. 1973.

8. Coe, W. B. and M. Turk. Processing Animal Waste by Anaerobic Fermentation. pp. 29-37 in Symposium: Processing Agricultural and Municipal Wastes. G. E. Inglett (ed.), Avi Publishing Company, Westport, Conn. 221 pages. 1973.

9. Halligan, J. E., K. L. Herzog, H. W. Parker, and R. M. Sweazy. Conversion of Cattle Feedlot Wastes to Ammonia Synthesis Gas. Environmental Protection Technology Series EPA 660/2-74-090, United States EPA, Corvallis, Oregon. 46 pages. 1974.

10. Hall, E. H., et al. Comparison of Fossil and Wood Fuels. Final Report from Battelle's Columbus Laboratories to the Environmental Protection Agency. Contract No. 68-02-1323, March, 1976.

11. Alich, J. A., Jr., and R. E. Inman. Effective Utilization of Solar Energy to Produce Clean Fuel. Report to National Science Foundation, NSF/RANN/SE/GI 38723/FR/74/2, Stanford Research Institute, Menlo Park, California. 161 pages. 1974.

12. Klass, D. L. A Perpetual Methane Economy - Is it Possible? Chemtech 4:161-168. 1974.

13. ERDA, 1976. A National Plan for Energy Research, Development and Demonstration; Creating Energy Choices for the Future, Volume 2: Program Implementation.

14. The Columbus Dispatch, February 8, 1976, p. K-1, and July 25, 1976, p. K-1.

15. Personal communication, Mr. Jim Shaffer, Public Utilities Commission of Ohio (September 2, 1976).

16. Huebler, J. 1975. Energy Overview, a paper given at Clean Fuels from Coal, Symposium II (June 23-27, 1975).

SECTION 2

INTRODUCTION

During the past decade in the United States, an awareness has developed that the highly specialized industrial and agricultural production that are this country's trademark are producing vast quantities of "waste" along with their primary products. During the late 1960's and early 1970's, there was a substantial effort, in both the public and private sectors, to develop technologies that could "dispose" of these materials in a manner less detrimental to the environment. As this effort matured, greater emphasis began to be placed on management systems and process technology that recovered usable material and/or energy from these wastes. The initial impetus for this waste recovery was to mitigate the rather substantial increased costs associated with improved disposal methods. As the energy shortfall from traditional fossil fuels became more apparent, this interest again shifted focus, and many of these systems began to be viewed for their energy capacities. Finally, it became apparent that many of these systems could be utilized to process other "feedstocks," which were not wastes per se but rather crops that were specifically cultivated for their energy conversion and chemical feedstock value. This whole field--including waste, as well as terrestrial and aquatic crop production--is now generally defined as Biomass Conversion Technology.

The foregoing discussion implies several features about this technology. First, with the possible exception of urban wastes, most of these materials are sparsely distributed relative to other established and developing energy sources such as coal, petroleum, uranium, etc. From this fact, it is concluded that an important factor dictating the economic use of these sources will be the efficiency with which they can be collected, concentrated, stored, and used.

Another important characteristic of most of these materials is their high initial moisture content. This characteristic places a substantial efficiency burden on many of the thermochemical conversion processes (e.g., those systems, including combustion methods, that substantially raise processing temperature to produce a desired chemical change) where a substantial portion of the energy content must be used to evaporate contained water. Consequently, the alternative approaches, which have been termed biochemical conversion processes (e.g., those systems which bring about desired chemical changes by the direct or indirect action of biological agents), appear at first glance, to possess distinct economic and source control advantages. The early stage of development of these technologies and the characteristically long storage times required for conversion to fuel products tend to offset these advantages. Furthermore, in some cases, downstream product purification often requires a water-fuel separation, partially negating the advantages achieved in the actual conversion step.

In terms of fuels, the most desirable feature of biomass as feedstock is its carbonaceous content. For most biomass materials, this can be interpreted as cellulosic content. Biomass sources also generally exhibit several additional favorable characteristics. Among the most significant, for sources other than urban waste and most ocean-grown aquatic crops, is the low ash and sulfur content that they exhibit. As a consequence, concentration of environmentally undesirable components, notably sulfur and heavy metals, is usually quite low.

The objective in undertaking this study was to develop a "preliminary environmental assessment of biomass conversion to synthetic fuels." The size of this report may suggest to some that it represents a more definitive document that in fact is the case. While the report contains large quantities of data and extensive analyses were undertaken, a conclusion that the work is beyond a preliminary stage would be erroneous. The scope of this report did not permit economic analyses, thereby limiting the conclusions regarding possible biomass sources, process technologies, and environmental controls to technical feasibility factors rather than economic feasibility factors. A review of the technical summary, conclusions, and recommendations confirms the substantial need for additional data and more in-depth analyses of important systems.

This report has been organized to present a review of the currently relevant technologies. To this end, the first two chapters deal with biomass sources and biomass conversion processes, respectively. These chapters have been developed in detail. The field of biomass technology is both broad and rapidly expanding. Consequently, the development of numerous crop species as potential feedstocks as well as new process configurations are anticipated.

Using the technological basis for commercialization of these technologies, it is then possible to begin to make preliminary estimates of the environmental consequences of biomass source development and process operations. However, this provides an incomplete basis as it overlooks environmental factors associated with feedstock and product collection, storage, and distribution, and certain socio-economic factors related to establishing large production facilities in previously agricultural and undeveloped settings. To analyze these factors, a series of scenarios was developed. The most prominent sources and processes were visualized in the context of a large production facility. For the purposes of this study, it was not necessary to develop these scenarios in great detail. However, characterizations that have been developed should be useful in preparing more comprehensive descriptions that might be required at a later date.

Finally, it was deemed important to assess the current plans of governmental agencies with relevant interest in biomass-energy technological developments. The breadth of the technology made it difficult to be assured that all programs had been reviewed, and as a practical matter, there probably were some oversights. However, the discussion included in this report should provide a worthwhile benchmark as of mid-1976 pointing to the expected direction of future development of biomass resources.

SECTION 3

CONCLUSIONS

The following conclusions highlight the more salient points identified during the course of this study on biomass resource development.

GENERAL

1. Biomass sources might reasonably be developed to satisfy 3 to 8 percent of the projected energy demand in the United States by the turn of the century.

2. In developing technology, emphasis should be placed on meshing biomass sources with localized energy needs. The biomass production/conversion process scenarios developed in this report provide an analytical technique that might be used in making the required judgments, and developing a basis for assessing environmental consequences.

3. Because of the limited resources likely to be available in developing these technologies, it is imperative that the activities of various agencies be well coordinated.

4. Since biomass to energy conversion technology is in an early stage of development, an excellent opportunity exists to assure that process technology and environmental protection develop simultaneously.

5. This preliminary study focused on the technological aspects of biomass production and conversion, and associated environmental effects. Additional data on the economics of production and of its attendant environmental protection is needed.

BIOMASS SOURCES

1. It is anticipated that the various biomass sources will be integrated into the synthetic fuels production industry within different time frames. The various biomass sources when ranked from nearest to longest term entry to such industry, are expected to follow the development order given below:

    - Urban and industrial waste
    - Agriculture and forestry wastes
    - Silviculture

- Energy crops
- Aquaculture

2. The potential amount of energy that is available from these biomass sources is significant. A conservative estimate of both energy pool and the net fuel potential which might reasonably be expected from these biomass sources is presented in Table 1. It is emphasized that these projections must be considered tentative.

3. It is apparent from the studies undertaken in this work that the availability of each of the biomass sources will vary by section of the country. It is possible to regionalize the country in a manner that permits identification of discrete biomass sources. Battelle's attempt at defining these regions and identifying some of the major biomass sources for each region are summarized in Tables 71 and 72 respectively.

4. The technology and economics of harvesting, collecting, storing and transporting large volumes of crop related materials to central locations have been poorly defined to date. Additional data is needed in this area. A more pragmatic technology development choice might be to reduce the size of operations to decrease the transportation distance, while concentrating on making localized areas independent of energy importation. Data on this option needs to be developed as well.

5. While economics were not addressed explicitly in these studies, it is anticipated that successful development of biomass resources will elicit strong competition from other industries, notably food, fiber and chemical manufacturers.

6. The major technological problem areas anticipated in relation to biomass sources can be generalized to (1) difficulties in raw materials storage, (2) crop seasonality, and (3) the energetics and logistics of harvesting and transportation.

CONVERSION PROCESSES

1. The development of biomass conversion processes, in many cases, has been initiated by earlier work in solid waste recovery activities.

2. Direct conversion systems are well developed and can (and probably will) be applied on a commercial basis to many biomass sources.

3. A host of pyrolysis conversion systems are under private and public development. Because of the versatility of the products, continued development should be encouraged.

4. Anaerobic digestion processes for methane production are receiving considerable attention, and do not appear to need additional concentrated support. However, most emphasis is on single-stage systems. Redirection of some of the effort towards multi-stage systems would seem appropriate.

5. Several new or revived technologies need more detailed study. These include hydrogenation, acid and enzymatic hydrolysis, naval stores processes, and fermentations not directed at methane. Feedstocks which should be emphasized include urban and agricultural/forestry wastes.

6. Ethanol fermentation is a well developed technology. However, historically, processes have been batch-operated. It is difficult to visualize processes directed at fuel production operated in batch modes. While difficulties in continuous fermentation are well known, process development along these lines appear necessary. These have been initiated, and should continue to be supported.

ENVIRONMENTAL ASSESSMENT

1. For all agricultural and forestry-derived biomass feedstocks, the overwhelming concerns relate to effects on land productivity and displacement when crops and crop residues are removed.

2. For processes operating on materials other than industrial waste and salt saturated aquatic crops, redispersal of process residuals to the land may be environmentally and technically sound. This area needs to be explored in more detail than was possible in this report.

3. For the most part, environmental control technology being developed for solid waste conversion processes should be applicable to other biomass feedstock, and is expected to represent typical case applications for biomass controls. Metal fume and heavy metal particulate removal and nitrogen oxide control from pyrolytic and hydrogenated liquids are the air pollution problems of most concern. Treatment of wastewater from processes such as anaerobic digestion and acid/enzymatic hydrolysis are significant water-related problem areas.

4. One disturbing fact which has arisen is the noted respiratory disease potential which occurs when bagasse is stored (see p. 45). Controlled storage methods need to be documented.

5. While only briefly addressed in this study, environmental and socioeconomic implications of locating large conversion plants in rural environments is a research area which needs attention.

6. Various global environmental concerns (for example, monoculture effects on ecological diversity and secondary productivity, changes induced by large plantations on solar reflectivity, wind currents, and other such variables) were beyond the scope of this study, but do need to be addressed before large scale implementation is undertaken. The near-term needs appear to be (1) definition of the problems and (2) collection of indicative data.

SECTION 4

RECOMMENDATIONS

This study reviews both production/conversion technological and environmental aspects of biomass production and its subsequent conversion to energy or fuel. The primary objective was to develop a preliminary environmental assessment and identify areas where environmentally related research is needed. Additional impressions however, evolved with regard to the needs of technology development. Since it is hoped that this report will be useful to a wide spectrum of readers interested in the various aspects of technological development, recommendations also have been included in this area as well. These recommendations are presented with the purpose of furthering the development of the state of conversion technology.

ENVIRONMENTAL RECOMMENDATIONS

1. A study, complementary to that described herein, needs to be undertaken with emphasis directed at specific economic aspects: (1) detailed development of cultivation, harvesting, transportation, and storage, and their associated costs, (2) first order approximation of the costs for production/conversion technology, and (3) first-order approximation of the costs of environmental controls. These data need to be assessed in an expansion of the scenario concept presented in this report, leading to a more quantified projection of the environmental and sociological implications, and associated costs.

2. A most pressing need identified is to undertake studies directed at quantifying the effect on land productivity and related variables of wholesale removal of biomass from the land. It is anticipated that the mitigating management practices can be developed. However, their development should precede, or, at the most, coincide with technology development in the production/conversion field.

3. As noted in the conclusions, storage of bagasse has been identified as a source of an agent which causes respiratory ailments. A detailed study should be undertaken identifying the limits of viability of the agents, related organisms that might cause similar ailments, the viability of the agents on major biomass crops that have been detailed in this report, and possible control measures.

4. Return of certain process residuals to the land may prove to be an environmentally and technologically sound practice. Studies directed at characterizing process residuals (such as insecticides, herbicides, etc.)

from the major conversion processes, when operated on crop-derived biomass, need to be undertaken.

5. The potential global effects of widespread biomass development could have important environmental and sociological effects. Studies need to be undertaken to address these effects. Objective definition of the nature of the problems, their potential effects, possible mitigating circumstances, and filling certain data gaps needs more research.

6. The possibilities of using nitrogen-fixing tree species for strip-mined reclamation, while producing a fuel-conversion crop warrants detailed investigation. The brief consideration given in this study suggests the environmental and potential energy recovery benefits greatly overwhelm unfavorable factors. However, clearer definition is required of the scope and implication of such activities before they are undertaken on a large scale.

RECOMMENDATIONS FOR PRODUCTION/CONVERSION TECHNOLOGY DEVELOPMENT

1. Harvesting and transportation technology will be crucial in biomass energy production activities. A study of the technological options including raw materials storage should be undertaken for each biomass category.

2. A study of localized (10-50 management) production/conversion alternatives is needed to provide a clearer comparison of the cost/benefit options to large scale developments.

3. Several of the less developed technologies need to be explored in more detail than was possible in this report. These studies should be substantiated with experimental data.

4. An experimental study of two-stage anaerobic digestion should be undertaken to provide data for a large-scale design and economic analysis.

SECTION 5

BIOMASS SOURCES

OVERVIEW

Most of the energy used in the U.S. comes from coal, oil, and natural gas. These are fossil fuels--energy-rich molecules resulting from photosynthesis in past geologic eras. As reserves of fossil fuels have been depleted in recent years, much interest in alternative energy sources has developed. Naturally some of that interest has focused on the photosynthetic process and the energy-rich organic material-biomass that results. The purpose of this chapter is to review the biomass sources potentially available for conversion into easily used, easily stored, clean burning fuels.

POTENTIAL BIOMASS SOURCES

There are many biomass sources. Two major categories are (1) energy crops and (2) wastes and residues. The former category includes vegetation, both terrestrial and aquatic, cultivated and managed expressly for the purpose of conversion into fuel. These energy plantations include aquaculture using kelp and other species, terrestrial energy crops such as sugar beets, and silviculture using productive species of trees. In addition to the possibility of growing and managing crops for energy, there is a large quantity of energy-rich organic wastes and residue from forestry, agricultural, and urban and municipal activities. This biomass source is of interest in that it may be possible not only to extract the previously unutilized energy but also reduce the costly treatment required to properly "dispose" or recycle some of these wastes.

This chapter will examine these potential biomass sources. The characteristics of the more productive species and the cultivation and harvesting techniques necessary for their growth will be discussed. Problems and limitations in their use as a fuel source will be examined. Finally, future trends for the use of these sources will be presented.

AGRICULTURAL AND FORESTRY RESIDUES

Initial Screening

Solid wastes from agricultural and forestry residues have been estimated to make up 73 percent of all organic wastes, including municipal and industrial wastes, generated annually in the United States.(1) The largest quantities of agricultural residues are in the form of portions of crops--stalks, leaves, vines, straw, stubble--that are left on the field after harvesting, and animal manure. The volume of forestry residues generated annually is considerably smaller than that of agricultural residues and consists of wood wastes remaining on the forest floor after timber removals, or accumulating at sawmills, pulpmills, and other wood processing industries.

Anderson(1) has calculated the quantities of organic solids ("organic solids" refers to the moisture- and ash-free fractions of the wastes) generated from various sources in the United States in 1971. He has also calculated conservative estimates of the proportions of these volumes which are in some way readily available at centralized locations; 4.5 million metric tons of forestry residues, 20.5 million metric tons of crop wastes, and 23.6 million metric tons of animal manures.

When a particular type of biomass waste happens to be available at centralized locations, it is more valuable as a potential feedstock for conversion to synthetic fuel since less energy needs to be expended in procuring it. For example, forestry residues are easy to collect from wood processing plants, as are manures from animals being raised in confined conditions. Residues from most agricultural crops are generally not available in large quantities at centralized locations, since after harvest operations they are not collected and therefore end up being uniformly distributed over fields covering many hectares. However, exceptions exist for a small percentage of the total crop residue volume. Bagasse and beet pulp accumulated at sugar mills, chaff from wheat at cereal grain mills, and other wastes from canning and food processing plants are typical examples.

Agricultural and forestry residues possess several unique advantages over other potential biomass energy feedstocks. In the first place, they are generated from the same large contiguous areas of land that are used to grow food or fiber so that it is not necessary to set aside land expressly for the purpose of producing them (as in the case of a biomass plantation). Also, many types of agricultural and forestry wastes are characterized by large percentages of carbon, moderately high heating values, and low sulfur content. They contain virtually no extraneous non-combustible materials such as glass, ceramics, or metal as would be found in urban refuse. Some forms of residue are produced in such large quantities that they become disposal and pollution problems. Manure is a disposal problem when the supply exceeds the demand for its use as a fertilizer. Clearly, the utilization of these wastes for synthetic fuel production would help solve the disposal problems while simultaneously creating a new source of energy.

Many forestry and agricultural wastes are presently being directly recycled back into the land, so that they are not really considered wastes. Forestry residues may remain on the forest floor to decompose and return nutrients to the soil, while creating niches and habitats for many types of wildlife. Manure has always been utilized as a fertilizer although a limit exists as to the amount in which it can safely be applied to crop soils. Grain and vegetable stalks are left for farm animals to graze upon and are eventually plowed down into the soil where they serve as soil conditioners. It should be considered that the above-ground portions of crop residues could probably be collected for energy purposes since the roots still remain to provide the soil with organic matter.

In recent years, crop harvesting methods have become increasingly mechanized so that as much residue as possible stays in the field instead of being unnecessarily transported to food processing facilities. Consequently, the total residue volume from some crop species is left in the field widely distributed over expansive areas. This means that more energy will be required to collect these residues, unless technological developments create a harvesting machine that can separate the food and the residue while harvesting them both simultaneously.

The three broad types of residues that show the most potential for conversion to energy are forestry residues, animal manures, and crop residues. Among the crop species, the ones that produce the largest volumes of residue per unit area are the grains, oilseeds, and sugar crops.

Forest Residues

Yields, Distributions, and Characteristics--

Forestry residues are wood wastes from two different sources, logging and milling. Logging residues or slash are the portions of trees which remain on the forest floor after logging operations have taken place in an area. They consist of tops of trunks, branches and leaves, and stumps. Residue may also result from stand improvement, when cull trees, rough and rotten or dead trees, undersize trees, and noncommercial species are removed from a woodlot or timber stand, and from thinning performed on growing stock. Milling or processing residues consist of slabs, shavings, trimmings, sawdust, bark, and log cores resulting from all processing operations occurring in primary and secondary manufacturing plants--especially sawmills, pulpmills, and veneer and plywood plants.

It is estimated(1) that about one-third of the volume of wood harvested in the United States each year is unused. Estimates of actual tons wasted vary considerably in the literature. The data in Table 3 are given for both logging and milling wastes for each of nine regions in the coterminous United States.(2)

Logging residues which are not collected at the same time as the harvested timber are almost always left on the ground unless disposed of by some means, usually by burning. Their lack of utilization is due to the energy expenditure that would be required in making a special effort to collect them, since they are composed of irregular shapes and sizes of material widely distributed over all types of terrain. New chippers have made it possible to utilize much more of this logging residue at the time of the primary harvest. However, Table 3 indicates that logging residues exist in large quantities in some regions in the country--notably in the South and in the Pacific states, where logging operations are extensive. For instance, one study(3) found that an average of 20 cubic meters (70 cubic feet), or about 14 metric tons (15 tons), of residue per acre remained on sites in Alabama where clearcutting has been completed. Residues are even more concentrated in the Douglas-fir region in Washington and Oregon,

TABLE 3. UNUSED WOOD WASTE AVAILABLE IN THE UNITED STATES, 1970[a]

Region	Logging Residues		Unused Primary and Secondary Milling Residues	
	10^6 metric tons	(10^6 tons)	10^6 metric tons	(10^6 tons)
New England (Me., Vt., N.H., Mass., Conn., R.I.)	10.4	(11.5)	2.6	(2.9)
Middle Atlantic (N.Y., Pa., N.J.)	6.7	(7.4)	1.6	(1.8)
West North Central (N. Dak., S. Dak., Nebr., Kans., Minn., Iowa, Mo.)	6.5	(7.2)	1.6	(1.8)
East North Central (Mich., Wis., Ind., Ill., Ohio)	14.6	(16.2)	3.7	(4.1)
South Atlantic (Md., Del., Va., W. Va., N.C., S.C., Ga., Fla.)	57.7	(63.6)	14.4	(15.9)
East South Central (Ky., Tenn., Ala., Miss.)	35.6	(39.2)	8.9	(9.8)
West South Central (Tex., Okla., Ark., La.)	34.8	(38.0)	8.6	(9.5)
Mountain (Idaho, Mont., Wyo., Utah, Nev., Colo., N. Mex., Ariz.)	17.1	(18.9)	4.3	(4.7)
Pacific (Wash., Oreg., Calif.)	74.7	(82.4)	18.7	(20.6)
	258.0	(284.4)	64.5	(71.1)

(a) Reference (2), p. 210.

where they constitute over 50 percent of all logging residues in the Pacific coast states including Alaska.(4) This is collaborated by other studies(5) which report that residues in the Douglas-fir region exist in ranges of 90 to 508 metric tons per hectare (40 to 227 tons per acre) after clearcutting has taken place in an area.

For various reasons amounts of logging residues have increased along with improved timber productivity in some areas. This may be a consequence of the increasingly mechanized harvesting procedures which have come into usage in the last decade and the decline in the practice of collecting scrap wood for fuel. In the Western states, in particular, residues appear to be accumulating in many areas.

Milling residues are a much more easily available source of material for potential energy uses than are logging residues because they are concentrated at processing plants instead of being scattered over wide areas. However, the sharply increasing demand for wood products in recent years has resulted in the creation of new products which utilize milling residues that formerly were wasted. In 1962, about half of all milling residues in the United States were wasted, but by 1970 this had decreased to about a quarter.(6) Particle board is a relatively new product which can be manufactured from residues, and it has found wide acceptance for use in many items where plywood, for example, was formerly required. Pulp for paper can also be produced from many types of milling residues as long as they are debarked.

Table 4 shows percentages of current uses for milling residues separately for wood and bark. Almost 70 percent of bark residues are unused, which is much larger than the 26 percent of unused wood residue. Bark comprises around two-thirds to three-quarters of all milling residues that are ultimately wasted.(7,8) By contrast, bark makes up only about 10 to 15 percent of felled timber and logging residues. More stringent air pollution regulations which limit the disposal of bark by burning have provided incentives to find new uses and products from bark. Some new products which have evolved are bark mulches, compressed fireplace logs, hardboard, and livestock bedding; bark is also used in the manufacture of charcoal and in smelting alloys. However, no single use has yet been found for bark to match the large quantities which are generated each year. One of its major drawbacks is that its chemical structure precludes its use in many pulp products, including paper.

Table 4 shows that a substantial proportion, 19 percent, of milling residues are already being used as fuel. In 1972, as much as 37 percent of the energy requirements of the pulp and paper industry were met through combustion of bark and pulp liquors.(4) Primary manufacturing industries, in general, are in a position to turn their own readily-available wastes into energy. Also, mills provide residues for use as fuel to several local electric-generating plants in the Pacific northwest. Although most of these plants are old and infrequently-operated facilities, one steam-electric plant in Eugene, Oregon, operated by the Eugene Water and Electric Board has been modernized and presently generates electricity eight months a year exclusively through the combustion of hogged wood and bark.(9) This plant is probably

TABLE 4. USES OF WOOD AND BARK RESIDUES PRODUCED BY PRIMARY WOOD PROCESSING PLANTS IN THE UNITED STATES, 1970[(a)]

Item	Percent
Uses of wood residues	
Pulp	47
Fuel	19
Other products (particle board, etc.)	8
Unused	26
	100
Uses of bark residues	
Industrial fuel and charcoal	23
Domestic fuel	4
Fiber products	1
Miscellaneous products and uses	3
Unused (burned or dumped)	69
	100

(a) Reference (6), pp. 33-34.

the exception, though it illustrates that a small proportion of milling residues are already being used as a fuel source for generating electricity.

Table 5 shows the results of chemical analyses of wood and bark from several tree species. Table 6 shows alpha-cellulose contents of the wood from a number of tree species. Alpha-cellulose is defined as lignin-free cellulose insoluble in 17.5 percent sodium hydroxide and in essence consisting of long chains of glucose molecules with beta-oxygen linkage between carbon atoms 1 and 4.(10) The alpha-cellulose contents and also the carbon contents do not vary much among tree species. Wood in general consists of 90 to 95 percent of all types of cellulose and 5 to 10 percent of volatiles, resins, fatty acids, minerals and other matter.(2) Wood cellulose has a heating value of 4610 kcal/kg (8,300 Btu/lb) dry weight, whereas the resins have a heating value of 9388 kCal/kg (16,900 Btu/lb). It is these resins which mainly account for the differences in the heating values of different species of wood. Thus, many softwoods which contain larger amounts of resinous material have somewhat higher heating values than do hardwoods (see also Table 5).

Water content has an extremely strong influence on the heating value of wood regardless of the tree species. Water has no caloric value, so the

TABLE 5. CHEMICAL ANALYSES OF WOOD AND BARK OF VARIOUS TREE SPECIES TYPES

Analyses (dry basis), % by wt	Wood and Bark						
	"Southern Pine" Bark[(a)]	Pine[(b)] Bark	Oak[(b)] Bark	Spruce[(b)] Bark	Redwood[(b)] Bark	Redwood[(b)]	Pine[(b)]
Proximate							
Volatile matter	66.0	72.9	76.0	69.6	72.6	82.5	79.4
Fixed carbon	33.4	24.2	18.7	26.6	27.0	17.3	20.1
Ash	0.6	2.9	5.3	3.8	0.4	0.2	0.5
Ultimate							
Hydrogen	5.5	5.6	5.4	5.7	5.1	5.9	6.3
Carbon	56.5	53.4	49.7	51.8	51.9	53.5	51.8
Sulfur	0.0	0.1	0.1	0.1	0.1	0	0
Nitrogen	0.4	0.1	0.2	0.2	0.1	0.1	0.1
Oxygen	37.0	37.9	39.3	38.4	42.4	40.3	41.3
Ash	0.6	2.9	5.3	3.8	0.4	0.2	0.5
Heating value, kcal/kg (Btu/lb)	4940 (8900)	5020 (9030)	4650 (8370)	4860 (8740)	4640 (8350)	5120 (9220)	5070 (9130)
Ash Analyses, % by wt							
SiO_2	19.0	39.0	11.1	32.0	14.3		
Fe_2O_3	1.0	3.0	3.3	6.4	3.5		
TiO_2	*	0.2	0.1	0.8	0.3		
Al_2O_3	21.0	14.0	0.1	11.0	4.0		
Mn_3O_4	*	Trace	Trace	1.5	0.1		
CaO	27.0	25.5	64.5	25.3	6.0		
MgO	5.0	6.5	1.2	4.1	6.6		
Na_2O	3.0	1.3	8.9	8.0	18.0		
K_2O	9.0	6.0	0.2	2.4	10.6		
SO_3	6.0	0.3	2.0	2.1	7.4		
Cl		Trace	Trace	Trace	18.4		
P_2O_5	4.0	*	*	*	*		

(a) Reference (12), pp. 36-37.

(b) Reference (2), p. 60.

* Analyses not included in the given reference.

water content in wood is negatively correlated with the caloric value of the green wood.

Water contents for green woods and densities for green and oven-dry woods are given in Table 7 for several wood species. Harvested wood can also vary in moisture content depending on how it is treated or stored. The water content of freshly-cut wood can be reduced from 50 percent to 25 percent in about a year simply by air-drying.(2) In fact, logging slash lying in the summer sun in western states dries to a 10 percent water content in only 2 to 3 weeks.(13) On the other hand, wood exposed to rain or humid conditions will increase in water content to values of 70 to 80 percent or more.

TABLE 6. CELLULOSE CONTENTS OF VARIOUS WOOD SPECIES[a]

Species	Alpha-Cellulose Content (% of Oven-Dry Extractive-Free Wood)
Red maple	44
Southern red oak	44
Quaking aspen	53
Paper birch	41
Balsam fir	45
Black spruce	46
Douglas-fir	48
Jack pine	42
Loblolly pine	47
Western hemlock	45
Western redcedar	48
White spruce	45

(a) Reference (10), p. 30.

TABLE 7. DENSITIES AND HEATING VALUES OF WOOD AND BARK OF VARIOUS SPECIES

Species	Oven-Dry Weight		Green Weight		Moisture Content-Wet Basis (percent)	Heating Value of Dry Weight	
	kg/m^3	(lb/ft^3)	kg/m^3	(lb/ft^3)		kcal/kg	(Btu/lb)
Douglas-fir, wood(a)	449	(28)	609	(38)	26	4950	(8,900)
bark	432	(27)	609	(38)	29	5450	(9,800)
Western hemlock, wood(a)	417	(26)	801	(50)	48	4650	(8,400)
bark	464	(29)	817	(51)	43	5200	(9,400)
Ponderosa pine, wood(a)	369	(23)	705	(44)	48	5050	(9,100)
bark	336	(21)	385	(24)	12	5050	(9,100)
White fir, wood(a)	369	(23)	753	(47)	51	4550	(8,200)
Western red cedar, wood(a)	321	(20)	—	—	—	5400	(9,700)
Lodgepole pine, wood(b)	385	(24)	—	—	—	4800	(8,600)
Red alder, wood(b)	369	(23)	—	—	—	4450	(8,000)
Oregon white oak, wood(b)	593	(37)	—	—	—	4500	(8,110)
Southern pine species, wood(c)	—	—	—	—	50	4950	(8,900)
Vermont forest residues (average representing expected species mixture)(d)	481	(30)	865	(54)	45	4700	(8,500)

(a) Reference (9), p. 13. , p. 13.
(b) Reference (11), p. 30.
(c) Reference (12), p. 36.
(d) Reference (2), p. 9.

Collection and Handling Methods--

Methods of collecting logging residues will probably have to be tailored to particular regions in the country if they are to be carried out on a continual basis and if they are to be profitable in the long run. Tree species, terrain, and primary harvesting methods used in a given region will be among the factors to determine which methods of collecting residues will be most productive and least expensive in a given area.

Several facts seem to be universally true with respect to collection methods. The first is that collecting residues can be much cheaper if as much is done as possible in conjunction with the primary commercial cut. For instance, in southern forests in particular, whole trees can be pulled with four-wheel drive skidders to *landing operations* before the tops are removed; then the tops and branches can be mechanically chipped and blown into a van. The chips will contain a mixture of wood and bark, making them unsuitable for many pulp products but not detracting from their value as a fuel source. Other forms of logging residues, such as non-commercial trees and defective boles, can often be brought to a central location using the same logging system that was designed for primary harvesting.

Another major consideration is that the minimum size requirement for the materials to be collected has a strong influence on the costs incurred per unit area. For example, the final yield per acre will be increased if all wood greater than 4 feet in length and 4 inches in diameter is to be collected in an area compared to the yield obtained if only those pieces greater than 8 feet in length and 8 inches in diameter are collected.(9) However, the costs incurred in yarding, loading, and transporting the smaller size materials will be substantially higher. A 1974 study(9) cites this cost as $1,960/ha ($793/acre) for the 8' x 8" minimum size material, as opposed to $3,066/ha ($1,241/acre) for the 4' x 4" minimum size material. This difference exists because primary harvesting equipment is not designed to handle small irregularly-shaped matter in an efficient way. Therefore, the collection costs will have to be weighed against the gains in residue volume in deciding what minimum size is acceptable.

In some western forests, a practice called yarding unutilized materials (Y.U.M.) has been initiated. This was brought about largely in response to pressure put upon lumber companies resulting from negative public reactions to the unsightly appearance of slash lying in large clearcut areas. Y.U.M. methods consist of bringing logging residues to centralized sites near roads so they can be deposited into relatively neat piles. This is carried out immediately after primary harvesting has removed the larger pieces of timber from the area. Y.U.M. practice has several advantages whether or not the piled-up residue is utilized for fuel or any other purpose. Aside from the esthetic standpoint, the isolation of the residue from the surrounding forest makes it more difficult for an outbreak of fire or pests to spread to the healthy standing timber. Presently, most Y.U.M. piles are simply burned under supervision or left to stand indefinitely. However, this method for spatially concentrating forest residues has a clear potential for making more material readily available for the production of energy.

Relatively little data are available to determine actual energy expenditures entailed in collecting and transporting residues. In a study by Battelle(2) these values were calculated in terms of Btu's expended to supply a 50-MWe electric plant with wood fuel over a period of a year (Table 8). It was estimated that this plant would consume a total input of 410,000 tons of wood per year. The energy expenditures required to collect, field process (chip), and truck-transport green wood in Vermont were given as 39,000 kcal/metric ton, 92,000 kcal/metric ton, and 300 kcal/metric ton-km (140,000 Btu/ton, 330,000 Btu/ton, and 1730 Btu/ton-mile), respectively. The energy expended per ton of wood for all three activities would then be a total of 0.16×10^6 kcal/metric ton (0.57×10^6 Btu/ton), assuming that the average transportation distance would be 65 km (40 miles). In the southern forest region, typical hauling distances to the nearest processing plant are reported to be less than or equal to 24 km (15 miles) for 50 percent of the available residue volume, and less than or equal to 48 km (30 miles) for 90 percent of the residue volume.(3)

Once the fuel is delivered to the plant, additional energy must be used if the wood is to be dried in a short time period. Presses can be used for this purpose, although energy costs can be cut by incorporating a design to utilize wasted hot air from boiler flue gas. Storage of wood chips over a length of time should not pose any substantial problems as long as they have been dried enough to prevent fungi from developing, and as long as they are stored in an area safe from fire hazards. Very small, dry wood particles like sawdust should not be stored indefinitely unless very thorough precautionary measures are taken to prevent spontaneous combustion.

Since wood has a relatively high heating value by itself and a certain amount of energy is always lost in conversion processes, it appears that an efficient use of wood energy can result when power plants directly utilize hogged wood fuel collected from local sources. Hogging is a hammer-milling process which renders the wood suitable for direct clean burning. There appears to be economic potential in the operation of steam/electric plants which can obtain wood from nearby mills or logging operations. However, the problem of obtaining the necessary volumes of residue impose an upper limit on the generating capacity of such an electric facility. One rough estimate is that about 1 ton (metric or English) of bone-dry, or 2 tons of wet, wood is required per hour to produce one megawatt-hour of electricity.(4) Because of this factor, some authors(9) conclude that an optimal generating capacity for an electric plant using hogged wood fuel would be 50 Mw. Below this size, scale economy is lost, and above this size, the quantities of residue necessary might not be available on a continual basis. The previously mentioned electric plant in Eugene, Oregon, has a generating capacity of 32 Mw. One conversion process that might extend the generating capacity up to 75 Mw is a gasification process using direct heating to produce low kcal fuel from residue volumes of 100-1,000 tons per day. Battelle(2) has determined that collection and other problems might put an absolute size limit of 200-250 Mwe on any single wood-fueled plant. Therefore, a generating plant with wood as its sole fuel might be ideally suited for providing electric power to small remote communities.

TABLE 8. ENERGY CONSUMPTION FOR COLLECTING, FIELD PROCESSING, AND TRANSPORTING LOGGING RESIDUES TO A 50-MWe ELECTRIC PLANT REQUIRING 370,000 METRIC TONS (410,000 TONS) PER YEAR(a)

Activity	Annual Energy Consumption kcal x 10^6	(Btu x 10^6)
Collecting residues from forest 372,000 metric tons x 39,000 kcal/metric ton (410,000 tons x 140,000 Btu/ton)	14,500	(57,400)
Field Processing with chipper 372,000 metric tons x 92,000 kcal/metric ton (410,000 tons x 330,000 Btu/ton)	34,200	(135,300)
Transporting by truck* 372,000 metric tons x 97 km x 300 kcal/metric ton-km (410,000 tons x 60 miles x 1730 Btu/ton-mile)	10,800	(42,600)
Total	59,500	(235,300)
Energy expended per metric ton (ton) for all activities	0.16	(0.57)

(a) Reference (2), p. 119.

* Using an average distance of 40 miles one way, equivalent to a weighted value of 97 km (60 miles) per round trip (64 km or 40 miles empty).

Wood processing industries are in a better position to utilize wood residues more efficiently when the energy content of the residues can be converted to steam energy instead of to electrical energy. The pulp and paper industry, for example, uses about 14 million kcal/metric ton (50 million Btu/ton) of paper produced. About 80 percent of this demand is required in the form of process steam for the pulping and paper-making operations.(9) Since under typical boiler conditions 1 kwh of thermal energy yields only 1/3 kwh of electrical energy, the energy value of wood is more effectively realized when direct conversion to steam is acceptable.

Projections of Current Trends and Recommendations--

Projections of current trends indicate that forest residue quantities will continue to increase along with increases in timber production. However, demand for timber products will also increase. Stephens and Heichel(10) estimate that the total timber demand for the year 2000 will be 0.57 billion cubic meters (20.3 billion cubic feet) whereas the anticipated growth of timber at the 1970 level of management will be 0.55 billion cubic meters (19.6 billion cubic feet). Grantham et al.(9) estimate that the demands for domestic wood by the year 2000 will show an increase of 0.21×10^9 m^3 (7.4×10^9 ft^3) over present consumption; 0.14×10^9 m^3 (4.9×10^9 ft^3) of this increase is expected to be supplied by logging residues and $.05 \times 10^9$ m^3 (1.8×10^9 ft^3) by milling residues. In short, the use of forestry residues for fuel will be in strong competition with the use of residues for wood, fiber, and chemical products. Even less waste will be accumulated at mills as new ways of utilizing mill residues are found, and as present utilization for such items as pulp and particleboard increases.

One response to the demand for more wood products will be an actual increase in timber volume. Stephens and Heichel(10) believe that timber production could actually be doubled through better, more intensive management, and that the Pacific forests in particular show the most potential for increased productivity. The southern region is also of extreme importance due to its large area of production.

It is very probable that, if new methods and equipment are developed for collecting logging residues, at least some of the material collected will be reclaimed for use in wood products since its value in commodities may be greater than its energy value. Therefore, new technology may be required to fulfill both types of needs. For instance, systems may be developed which will concentrate logging residues at a roadside and then separate them into two categories depending on their subsequent use. New equipment will be needed to deal with small, irregular pieces and perhaps to sort them into size classes, debark larger pieces suitable for pulp, chip the smaller branches as well as larger cull trees usable only for fuel, and so on. Bark is still one form of residue which can be readily collected from processing mills and for which there is presently not much demand. As an example of future yields, production of southern pine bark is expected to reach 9 million metric tons (10 million tons) a year by the year 2000.(12) Bark wastes can clearly be utilized for fuel immediately without prior technological advancements.

In summary, wood is a valuable energy source because of its high Btu content and its clean-burning fuel properties. However, most of the residues easily obtainable from processing plants are probably utilizable for other higher value products, and residues from logging operations are so scattered over large areas that a major investment of energy is required to collect them. If the gathering of logging residues is to be economically profitable, it will require major improvements in harvesting systems (e.g., to coordinate residue collection with primary removal operations) and technological developments to make present equipment more adaptable. Some motivation to effect these changes may already be provided by certain problems not related to the search for new fuels. For example, logging slash in the West, in particular, is a serious fire hazard during dry months as well as a breeding site for pests and diseases. Also, slash has to be removed in areas of short-rotation forestry if a plot of ground is being prepared for new plantings.

A more complete utilization of forest residues for both wood products and fuel is necessary. This will undoubtedly require a more intensive and far-sighted level of management in all phases of forestry.

Animal Manures

Yields, Distributions, and Characteristics--

Animal manures are being produced at the rate of 1.4-1.8 billion metric tons (1.5-2.0 billion tons) per year in the United States,(1) making them one of the largest sources of organic waste. Their value as a potential energy feedstock owes to their availability in large quantities which are continually being generated in centralized locations, and to the fact that they are often the source of solid waste disposal and water pollution problems. If fuel production from animal wastes could be made economically profitable, farmers would be motivated to provide conversion plants for animal wastes. The potential for added income from the fuel produced, controlled fertilizer production, and the advantage of having a dependable means for disposing of the non-recycleable wastes present opportunities for extensive environmental control.

Table 9 presents estimated quantities of solid organic wastes produced by the four major farm animals in the United States in 1971. Organic solid wastes are defined as moisture- and ash-free waste materials, and the values were calculated on the bases of expected percentages of these solids in the total weight of wastes excreted from each type of animal. From Table 9 it is to be noted that organic solids from cattle wastes make up the great majority (88 percent) of that from all major farm animals.

About 50 to 80 percent of all farm animals are in confined conditions.(1) This is especially true of cattle, since they are either dairy cattle residing in intensively-organized milk producing operations, or beef cattle which are being raised in increasingly large feedlots in the southwestern and southern plain states. Table 10 shows the numbers of feedlots of various size ranges in the United States in 1962 and 1970. The largest feedlots (8,000 or more head/lot) are the fastest-growing lots, and there is also a dramatic increase in the absolute numbers of these feedlots.

TABLE 9. WASTES GENERATED BY MAJOR FARM ANIMALS IN THE UNITED STATES, 1971(a)

		Amounts of Solid Organic Waste Generated*			
Animals	Numbers of Animals in U.S. (Thousands)	Kg (Lbs)/Each Animal/Day		Metric Tons (Tons) x 10^6/ All Animals/Year	
Cattle	114,568	3.72	(8.20)	156	(172)
Hogs	67,540	0.41	(0.91)	10.2	(11.3)
Sheep	19,560	0.21	(0.46)	1.49	(1.64)
Poultry	1,116,680	0.02	(.047)	8.65	(9.54)
				176.4	(194.5)

(a) Reference (1), p. 5.
* Moisture- and ash-free.

TABLE 10. GROWTH IN NUMBERS OF LARGE BEEF FEEDLOTS IN THE U.S. FROM 1962 TO 1970[a]

Feedlot Size	No. of Feedlots 1962	No. of Feedlots 1970	Total No. of Cattle in Feedlot Size Range (Thousands)[b] 1962	Total No. of Cattle in Feedlot Size Range (Thousands)[b] 1970
1,000 - 2,000	752	1004	900	1250
2,000 - 4,000	373	549	850	1500
4,000 - 8,000	179	333	1100	1900
8,000 - 16,000	105	210	1450	3100
16,000 - 32,000	26	105	800	3200
over 32,000	5	41	300	2800

(a) Reference (14), p. 31.
(b) Reference (1), p. 10; values extrapolated from graph.

Four areas now contain at least 400,000 cattle each concentrated in lots of 10,000 or more head apiece: Lubbock, Texas; Casa Grande, Arizona; Greeley, Colorado; and Bakersfield, California.(15) The Texas panhandle cattle-growing region has an average density of about 200 head/km^2 (500/square mile); 3.6 million cattle were fed there in 1970.(16) The Greeley, Colorado area has two feedlots with 100,000 head apiece, believed to be the largest beef feedlots in the world. Other large feedlots are located in parts of Oklahoma, Kansas, Nebraska, Iowa, and Nevada.

Cattle produce large volumes of waste because they do not convert food very efficiently; an average animal being fattened on a beef feedlot gains about 1.0-1.5 kg (2-3 lbs) of weight a day, whereas it excretes 22-27 kg (48-60 lbs) of waste a day. About 85 percent of this waste is water, and about 75 to 80 percent of the dry solids are volatile solids. A chemical composition analysis is presented in Table 11.

Collection and Handling Methods--

The type of manure disposal method employed depends on the type of farming operation (beef or dairy cattle) and the region of the country. Disposal systems tend to divide into two categories: solid disposal and liquid disposal systems. Of the two types, liquid disposal systems generally cost more.

Liquid disposal is common in dairy operations and/or in the colder and damper climatic regions of the U.S. In this system, fresh liquid manure is pumped through a sewer system into a ditch, septic tank, pond, or lagoon, where bacterial decomposition takes place over a prolonged time period.

TABLE 11. CHEMICAL COMPOSITION OF FRESH MANURE FROM BEEF CATTLE[(a)]

Constituent *	Percent of Wet Weight
Water	85.0
Dry Solids	15.0
Volatile Solids	11.9
Ash	3.1
Carbon	7.5
Nitrogen-organic	.32
Phosphorus	.06
Potassium	.15
Calcium	.15
Magnesium	.06
Sodium	.15
Sulfur	.05
Iron	.06

* pH = 7.3

Density of dry manure = 0.96 kg/l (60 lbs/ft^3)

Heating value of dry manure = 3429 kcal/kg (6173 Btu/lb)

(a) Reference (17), p. 5; Reference (18), p. 31; Reference (19), p. 19, Reference 14, p. 119.

The biochemical process involved is aerobic or anaerobic, often by default depending on the dissolved oxygen concentration in the pond. The solids settle to the bottom and can eventually be pumped out. In some cases the liquid can then be used to directly irrigate cropland through use of large sprinklers or sprayers.

In other dairy operations, the solid disposal system is employed. Cows are bedded with straw, sawdust or mulch. The manure, which becomes mixed with and partially absorbed by the bedding, is removed daily and stacked to dry for a few months before hauling. This is an example of one solid disposal system utilized by smaller operations. Other types of solid disposal are used extensively on the large beef feedlots in the southwestern United States. Manure excreted on the open ground dries very quickly and odor is minimal as long as the weather is dry. Then it can be scooped into mounds where aerobic composting processes take place rapidly--in the hot dry conditions the mounds smolder and smoke from the heat of the composting reactions. Several times a year it is loaded into trucks with front-end loaders and hauled to farmers for use as fertilizer. Large feedlots are also required to have lagoons which can accommodate runoff that takes place during the wetter winter months.

In the Greeley, Colorado, feedlot area, grain farmers sometimes receive an allotment of manure for use as fertilizer in relation to the amount of grain they sell the feeders, and the farmers do their own hauling. In Texas, Arizona, and California, manure is handled by contractors who invest in the large equipment necessary to haul and transport the manure, sell it to the farmers, and spread it on the field. However, in the areas surrounding the large feedlots in these latter three states, the supply has been exceeding the demand in recent years, so the excess manure remains stockpiled on the feedlots. Overfertilization of crops and soil salinity problems result when manure is over-applied to croplands. Consequently, none of the contractors in these areas have been netting profits from their manure-handling systems in recent years, though exact data on costs incurred for loading and transportation of manure are not presently available. A recycle system should address salinity removal benefits as well as environmental control of the balanced application of land use chemicals and conditions.

Projections of Current Trends and Recommendations--

Various experimenters using cattle manure in anaerobic digestors have reported that volumes of .30-.55 cubic meters of "biogas" can be produced from each kilogram (5-9 cubic feet from each pound) of volatile solids present in the input material, and an average of 60 percent of this gas is methane.(14,20) At least three firms in the United States have announced plans for the construction of pilot plants to produce methane by anaerobic digestion of livestock manures. These will be located in Lubbock, Texas (operated by Ecological Research Associates, Inc.): Optima, Oklahoma (Calorific Anaerobic Processes, Inc.); and Greeley, Colorado (BioGas of Colorado, Inc.). The production capabilities of each of these conversion processes will be 18×10^6 m^3 (650×10^6 ft^3), 18×10^6 m^3 (650×10^6 ft^3), and 24×10^6 m^3 (840×10^6 ft^3) of synthetic natural gas per year, respectively.(21) The Ecological Research Associates are the originators of the HYMETH, or high-quality methane generating process. Their proposed Texas pilot plant will utilize 8.5-17.0 metric tons (9.5-18.5 tons) of cattle waste from a nearby feedlot in order to determine optimal operating characteristics of the process.(22) In addition, the Biomass Energy Institute of Canada started operating a pilot plant in 1971 which produces methane from manure obtained from swine barns maintained by the University of Manitoba.

Much technological work remains to be completed with regard to the conditions necessary for stable, optimal methane production from anaerobic digestors. If successful processes are developed, systems for collecting the manure for the digestors will probably have to be improved also. The solid disposal systems so widely used in large feedlots in the southwest, in particular, may have to be modified considerably if they are to provide feedstock for large-scale methane production. This is because their present handling methods consist of letting the manure become dried and biochemically degraded before collecting it, whereas fresh manure which still contains high levels of volatile solids is a much more productive source of methane. One experiment with dairy manure showed that digestors produced 2.3 times as much gas using fresh manure containing its original moisture as using aged manure.(23) Therefore, collection of feedlot manure for methane production may be required on a more frequent basis than is currently being employed. This will entail greater expenditures of energy for collection and hauling since fresh manure has a greater weight due to the high moisture content. These added costs will have to be measured against the benefits of increased methane production.

In the liquid disposal systems presently used in this country, methane is constantly being generated from the natural anaerobic processes taking place in the holding ponds and lagoons incorporated into the systems. So far, however, this methane is simply escaping into the surrounding environment because it has not appeared economical to invest in the equipment necessary for collecting it.

Projections of current trends(1) indicate that by 1980 the annual production of solid organic wastes from cattle in the United States will be 213 million metric tons (235 million tons). This waste will be generated in increasingly concentrated locations because the largest feedlots are now the fastest-growing feedlots, and even dairies with around a thousand head are common. These various factors all demonstrate the enormous potential of livestock manures towards synthetic fuel production.

The use of manure residuals as a fertilizer may increase as the costs of chemical nitrogenous fertilizers (which require fossil fuel energy in their manufacture) continue to rise. It is fortunate that the use of manure for fuel production need not compete with its use as fertilizer. The anaerobic processes which produce methane are such that, after completion, a large fraction of the original weight of the manure is left in the form of humus-like residues and liquors that are rich in nitrogen.(16) In other words, the nitrogen value of the manure, while low, remains intact, and could be recycled after processing.

Crop Residues

Yields, Distributions, and Characteristics--

Crop residues are produced in tremendous volumes each year in the United States, mostly becoming available after the harvest season in the fall. It is estimated that the total production is about 350 million metric tons (390 million tons) of organic solids (moisture- and ash-free solids) each year.(1) Grain and oilseed crops, particularly corn, wheat, and soybeans, are responsible for a large proportion of this production because they are grown on millions of acres and because their biomass yields per unit area are also large. Sugar crops like sugarcane and sugar beets are only grown on a small fraction of the United States cropland but they are capable of producing exceptionally large yields of residue per unit area. Table 12 summarizes these yields for six selected crop species.

Grain and oilseed crops generate residues in the form of leaves and stalks distributed uniformly over the field from which the grain or seeds were harvested. Residues like these which remain on the fields account for 94 percent of the organic solids produced annually by crop residues. The remaining 6 percent are from wastes available at centralized locations such as sugar refineries, mills, canneries, and other food processing plants. Residues from sugar crops, namely bagasse from sugarcane and pulp from sugar beets, fall into this latter category because the entire canestalk or beet must be transported to the sugar mill after it is harvested in order to extract the sugar. In the case of corn or soybeans grown for silage, no substantial volumes of residue are produced because there the entire stalk is harvested and cut up to be used for animal consumption.

The most common practice for processing residual crop materials, like cornstalks left on harvested fields, is to plow them back down into the soil before the next planting season. This organic material, essential in crop rotation systems, is an important soil conditioner because it improves the air- and water-holding capacity of the soil and it reduces wind and water erosion. Hay, straw, and leaves are also used as food or bedding for farm livestock. Sugar beet pulp is processed and sold as an animal nutrient supplement. Sugarcane bagasse has shown limited use in the manufacture of fiberboard and acoustical wall-board, and in some areas it is burned to fuel the boilers of the sugar refineries where it originates. Corn cobs are used to manufacture chemicals or are ground into abrasive particles for polishing or blasting.

Table 13 presents water, ash, carbon, and sulfur contents of various crop components. The carbon contents given correspond to ultimate chemical analysis results, though they should not be construed as precise values because they were calculated from nutritional data. Cellulose contents in herbaceous plant stalks can generally range anywhere from 25 to 60 percent, with alpha-cellulose contents ranging from 15 to 40 percent;(26) however, the carbon contents of the crops shown in Table 13 fall into the more consistent range of 33 to 42 percent. Heating values for dried stalks of corn, wheat, and many other crop species are on the order of 3600 kCal/kg (6,500 Btu/lb).(27) Dried bagasse has a larger heating value of about 4400 kCal/kg (8,000 Btu/lb), close to that of wood. Table 14 gives chemical

TABLE 12. YIELDS, PRODUCTION, AND DISTRIBUTIONS OF RESIDUES FROM SELECTED CROP SPECIES[a]

Crop Residue	Residue Yield (metric tons/ha)[a,b]	Millions of Hectares Harvested (1974)[b]	Total Residue Production (millions of metric tons)	Percent of Total U.S. Food Production by Top Five States[b] (1974)
Wheat (straw, stubble)	3 - 3.5	26.5	80 - 93	50.2 (Kans., N. Dak., Okla., Wash., Mont.)
Corn for grain (leaves and stalks)	6 - 10	26.4	158 - 264	62.5 (Iowa, Ill., Ind., Nebr., Minn.)
Sorghum for grain (leaves and stalks)	6 - 7	5.6	34 - 39	88.3 (Tex., Kans., Nebr., Okla., Mo.)
Soybeans for beans (leaves and stalks)	4.5 - 5	21.2	95 - 106	55.6 (Ill., Iowa, Ind., Mo., Ark.)
Sugarcane for sugar (bagasse)	20 - 25	0.3	6 - 7.5	100.0 (Hawaii, Fla., La., Tex.)
Sugar beets (pulp)	8 - 15	0.5	4 - 7.5	62.2 (Calif., Colo., Minn., Idaho, N. Dak.)

(a) Reference (10), p. 32.
(b) Reference (24), pp. 1-130.

One hectare = 2.471 acres
One metric ton = 1.102 tons
One metric ton/hectare = 0.446 tons/acre

TABLE 13. CHEMICAL PARAMETERS OF SELECTED CROP RESIDUES[(a)]

Crop Residue	Water-% wet weight	Ash-% dry weight	Cellulose-% dry weight	Carbon-% dry weight	Sulfur-% dry weight
Wheat straw	12.2	7.2	43.6	39.3	0.18
Corn cobs	9.6	1.8	35.5	41.8	0.47
Corn stalks and leaves	15.6* 66.4**	7.3	33.4	38.8	0.17
Sorghum stalks and leaves	9.7* 67.0**	8.6	20.5	37.9	—
Soybean hay	8.9* 77.3**	7.3	35.8	39.7	—
Sugarcane bagasse	8.5* 50.0**	3.1	48.6	40.9	—
Sugar beet leaves	84.1**	20.6	10.7	32.9	0.57
Sugar beet pulp	88.7	4.7	30.1	39.9	—

* Sun-dried after harvesting
** Fresh
(a) Reference (25), pp. 104-105.

TABLE 14. CHEMICAL COMPOSITION OF HARVESTED AND FIELD-DRIED BAGASSE AND RICE STRAW

Composition	Bagasse as Harvested(a)	Bagasse Field-Dried(a,b)	Rice Straw(c)
Proximate (%)			
Moisture	52.0	15.0	
Volatile	40.2	71.2	
Fixed carbon	6.1	10.8	
Ash	1.7	3.0	
Ultimate (%)			
Moisture	52.0	15.0	7.4
Hydrogen	2.8	5.0	5.1
Carbon	23.4	41.4	33.6
Nitrogen/oxygen	20.1	35.6	37.3
Sulfur	Trace	Trace	0.1
Ash	1.7	3.0	16.5
Heating value			
kcal/kg	2,200	3,930-4,590	3,370
(Btu/lb)	(4,000)	(7,080-8,260)	(6,080)
Bulk density, stacked(d)			
kg/m^3		200.4	192.4
(lbs/ft^3)		(12.5)	(12.0)

(a) Reference (28), p. 98.
(b) Reference (29), p. 164.
(c) Reference (30), p. 97.
(d) Reference (31), p. 68.

analyses in more detail for bagasse and straw.

Collection and Handling Methods--

Crops grown for grain or seed are presently harvested through highly mechanized procedures that avoid transporting unusable residues out of the field. Agricultural statistics for Illinois, a top corn-producing state, show that the percent of corn acreage harvested by mechanical pickers (which collect the whole corn cob from the stalk) decreased steadily from 80 percent to 13 percent over the years from 1960 to 1975. Over this same time period, the use of combines and picker-shellers (which collect only the corn and leave the cob in the field) increased steadily from 18 percent to 87 percent.(32) Harvesting procedures for other crops have shown similar trends; consequently, the great majority of the total crop residue is left distributed over millions of acres of cropland.

Data are not available regarding the energy that would be required specifically to collect this material. Thus far, there has not been economic incentive for anyone to actually do this. However, due to recent interest in the nutritional value of corn stalks for livestock, some agricultural equipment firms have started developing harvesting combines which will harvest the grain and the residue simultaneously, while grinding and compressing the stover into a van separate from the one containing the grain. This type of equipment would have obvious potential application towards collecting residues for conversion to synthetic fuel as well as for food, because it would eliminate the need to make an additional expedition over the field for the express purpose of collecting the residues.

Table 13 indicates the extent to which crop parts become dried by the sun while lying in the field. However, plant material is still very perishable even after dehydration. Present methods for handling the large quantities of bagasse that accumulate at sugar mills in the United States, consist of treating the bagasse with fungicides and forming it into bales which are piled outdoors. The piles are covered to keep out rainwater and are specially constructed to permit ventilation and drying. However, the effect of deterioration of the bagasse by weather conditions and microorganisms produces a dust that is capable of causing a peculiar respiratory disorder when inhaled. Similar types of problems would probably place limitations upon the lengths of time and the quantities in which any species of crop residues could be stored.

Projections of Current Trends and Recommendations--

Agricultural production has substantially increased over the past two decades, not because marginal land has been converted into cropland but because new hybrids and improved agricultural technology have increased the yields per acre for many crop species. As the food productivity from crops increases, so do residue volumes. Combines that collect food and residues simultaneously will be essential if the utilization of residues as an energy source is to be made economically feasible. Such combines are being developed, but their development was motivated by the increasing costs of livestock feed. Fertilizer costs are also increasing, so the potential use of crop residues for fuel will have to compete with their use for feed and green manure.

Still, the total crop residue volume produced annually is so large that there may be a sufficient supply for all these purposes. Storage problems and its limited seasonal availability may be the factors which utlimately place the heaviest restrictions upon the use of crop residues for energy production. Feasibility may depend on a biomass conversion process which (1) can be implemented on a local level so that farmers do not have to transport bulky residue volumes long distances, and (2) operates quickly enough so that entire fields of residue can be converted to fuel soon after collecting and drying. This would eliminate residue storage problems and the fuel produced would be simpler to store until it could be supplied to meet local energy needs.

AQUACULTURAL PRODUCTION

Initial Screening

The productivity of plant biomass is higher in aquatic systems than in terrestrial systems. Thus, particular attention needs to be placed on biomass sources from both freshwater and saltwater media. Leith's(33) review of energy fixation of the major vegetations units of the world shows the following trends:

TABLE 15. AQUATIC PLANT PRODUCTIVITY IN MAJOR WORLD HABITATS

Habitat	Mean-kg (dry)/ m^2/yr (lb/ft^2/yr)	Range
Marine		
open ocean	0.13 (0.03)	0.002 - 0.4 (0.0004-0.08)
continental shelf	0.36 (0.07)	0.2 - 0.6 (0.04-0.12)
algal beds and reefs	0.6 (0.12)	0.5 - 4.0 (0.10-0.82)
estuaries	1.8 (0.37)	0.002 - 4.0 (0.0004-0.82)
Freshwater		
swamps and marsh	2.0 (0.41)	0.8 - 4.0 (0.16-0.82)
land and stream	0.5 (0.10)	0.1 - 1.5 (0.02-0.31)

The most productive zones are estuaries, swamps, and marshes. In addition to these natural production systems, managed aquatic systems whose productivity is high includes the culture of algae and kelp.

This characterization focuses on three kinds of biomass sources. Natural production sources will include marsh plants, especially highly productive salt marsh species. The other two biomass sources are from managed systems of algal culture, including kelp and water hyacinth.

Marsh Plants

Distributions and Yields--

Marshlands or wetlands border the coastlines and river margins of the United States. Extensive wetlands occur in Florida, Louisiana, and Georgia. For example, 1,520,000 hectares (3,750,000 acres) of coastal marshes are found in Louisiana(34); the saline, brackish and freshwater marshes extend 80-97 km (50-60 miles) inland in certain parishes. There are smaller marshes in the northeast, northwest, and Great Lakes region.

Primary production of marshes is high when compared to production in terrestrial communities.(35) Four of about 25 species of plants exhibit high production:(36) smooth cord grass (Spartina alterniflora), common reed (Phragmites communis), bulrush (Scirpus spp.), and cattail (Typha spp.). A profile of their highest observed production and locales are shown in Table 16. These totals range from 19 to 64 metric tons dry weight

TABLE 16. BIOMASS PRODUCTION FOR FOUR SPECIES OF MARSH PLANTS

Species	Above Ground Production kg (dry)/m^2/yr	(lb/ft^2/yr)	Locale	Source
Spartina alterniflora	2.000-2.300	(0.410-0.471)	Georgia	Odum(35)
Phragmites communis	2.695	(0.552)	Long Island	Harper(39)
Scirpus lacustris	6.400	(1.311)	Germany	Seidel(40)
Typha latifolia and T. angustifolia	1.905	(0.390)	New Jersey	Jervis(41)

biomass/hectare/year (8.5-28.5 tons/acre/yr).

Production of these species generally decreases from south to north. Figure 1 shows this general trend. This means that higher yields will be found in California, Florida, the Gulf states and Georgia than states further north.

Elemental compositions of these marsh plants(36) are provided in Table 17. Percent carbon averages about 44, percent nitrogen (N) about 2, and phosphorus (P) <1. Carbon-to-nitrogen ratios are 20-30 and a little below the range (30-40) for terrestrial plants.(37) Variations in percent N and P reflect nutrient availability in the environment.

TABLE 17. ELEMENTAL COMPOSITIONS OF SELECTED MARSH PLANTS

Species	Percent C	Percent N	Percent P	C:N (atomic)
Spartina alterniflora	43.0	1.6	0.3	26.9
Phragmites communis	-	1.8	0.1	-
Scirpus lacustris	-	-	-	-
Typha latifolia and T. angustifolia	44.9	2.1	0.2	21.4

The values are averages of individually reported studies; the number of studies ranges from 1 to 13 for a given cell of information.

Studies of energy flow reveal that Spartina sp. in Georgia accounts for 2/3 to 3/4 of the plant production in the marshes.(38) In this and three

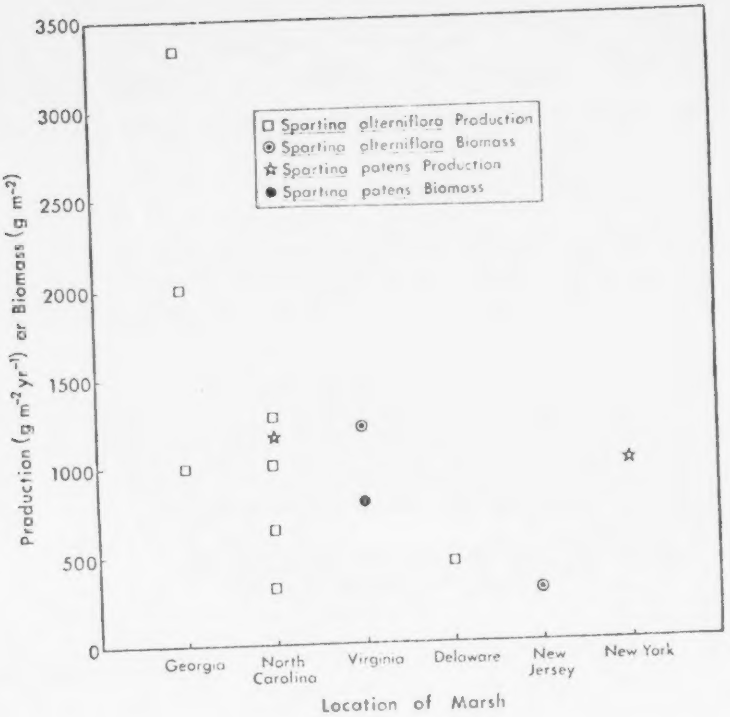


Figure 1. Comparison of production and biomass estimates of Spartina alterniflora and Spartina patens along a south to north gradient in Atlantic coast marshes.(36)

other marshes, efficiency of conversion of incident radiation to biomass is less than 1 percent. However, the large amounts of biomass produced compensates for the seemingly inefficient energy conversion.

Current uses of these marsh plants reflect their role in ecological systems rather than their direct consumption as human food or fuel per se. Wetland vegetation buffers the mainland from erosion by storms and tides. The decomposing marsh plants form the basis for many of the nearshore foodwebs, including shellfish and shrimp. Also, the marsh plants provide food and cover for many species of waterfowl, furbearers, and nurseries for many marine organisms.

Cultivation, Harvest, and Storage--

Planting and cultivation practices are well developed, particularly for Spartina alterniflora.(42) Machines to harvest seeds, prepare soil and transplanting are used if the substrate is firm. Experiments have shown that single stems should be spaced 2.3 cm (0.9 inch) apart. The best months for transplanting are in the spring, although it may be done during other seasons. Seeding can be done at the rate of 100 seed/m^2. (11 seeds/ft^2) After two growing seasons, artificially propagated marshes are little different from long-established natural marshes. Addition of nitrogen and phosphorus fertilizers can increase growth.

The life form of the four species of marsh plants is a slender stalk of relatively soft tissue from 0.6-1.2 m (2-4 ft) tall. Stands of marsh plants number 700-1000 shoots/m^2 (65-93/ft^2)(43) and are essentially mono cultures. For example, cordgrass grows as a single species community in salinity ranges beyond the physiological ranges of most plants.

There is an annual die-back each year in the fall and winter, but since the plants are perennials new shoots grow from root stock each spring in temperate zones. Fungi attacks the decomposing plants. The presence of water also accelerates physical deterioration.

There are no known studies on energy costs of harvesting marsh plants. Indeed, harvest methods are not well developed. Cattle grazing and mowing of pump-out pastures are practiced, however.

Projections of Current Trends and Recommendations--

Harvest methods for marsh plants are not well developed. One of the major engineering obstacles of harvesting marsh plants is the manufacture of marsh buggies or hover craft that minimize compaction damage to the soft, mucky soils of marshes.

The wetland vegetation, particularly salt marshes, represents an extensive, good biomass source from an environment in which only these particular plants can grow. Future use of marsh plants for fuels must be tempered by the realization of the ecological value of intact, natural wetlands and the laws and regulations that control their development. Because of the limited range of the species on the natural aesthetic appeal of wetlands, it does not appear a good prospect for major fuel conversion effort.

Water Hyacinth

Distributions and yields--

Water hyacinth (Eichhornia crassipes) grows in subtropical and tropical regions of the world. Thus, in the United States it is concentrated in the southeast, particularly in the area of the lower Mississippi River and its distributaries.(44) The plant is considered a weed since it grows rapidly and chokes many navigational canals.

The productivity of water hyacinth is not well established for typical growing conditions. Maximum production occurs in the period March through October and attains standing crops of about 25 metric tons/hectare (dry wt).(44) Projected values for productivity are about 150 metric tons/hectare/year.(45) This projection assumes optimum growth conditions. Actual productivity under natural conditions would be much less than this projection.

Boyd and Blackburn(46) reported that percent dry matter for water hyacinth averages about 6, while cellulose is about 23 percent dry weight. They also show that proximate composition of water hyacinth varies by season. Parra and Mortenstine(47) reported that environmental conditions also cause the composition to vary from place to place. Mean chemical compositions from 19 locales in Florida are shown in Table 18. Note that carbon is about 1/3 the dry weight biomass.

The most important limiting factor is temperature. The plant is highly susceptible to frost and exposure to temperatures above 34 C. Water hyacinth does not grow in water whose salinity is greater than 15 percent of seawater. Also, dissolved oxygen and pH (3-10 range) affect growth.

Water hyacinths have little or no commercial use at present. Indeed, considerable effort is spent on their eradication. However, there are several proposed uses, e.g., compost, cattle feed, and living filters in sewage treatment.

Cultivation, Harvest, and Storage--

Propagation by man is generally not deliberate. The plant reproduces two ways. About 50 seeds per capsule are deposited on the hyacinth mat or sink to the bottom of the waterway where they germinate. Rhizomes produce vegetatively, doubling in approximately 2 weeks.(44)

Harvest procedures are not well developed. Presumably, large suction devices could slurp up hyacinth mats. To assure continued propagation via rhizomes, an underwater cutting device may be another must. Barges could be mounted with harvesting devices including drying kilns.

Storage must consider the water content which is about 95 percent. It would be necessary to dry the plants to reduce the problems of decomposition.

Projections of Current Trends and Recommendations--

Attitudes toward water hyacinth as a noxious water weed can be altered. The plant can be used as a biomass source for fuels. Since water hyacinth

TABLE 18. CHEMICAL COMPOSITION OF WATER HYACINTH

Element	Chemical Composition (% dry wt)
Aluminum	0.3
Calcium	1.7
Carbon	34.9
Chromium	<.01
Copper	<.01
Iron	0.4
Magnesium	0.6
Manganese	0.01
Nitrogen	1.6
Phosphorus	0.3
Potassium	3.8
Sodium	0.6
Zinc	<0.01
Ash	19.2
C/N ratio	23.3

uptakes many elements, the plant is also a candidate for living filters in sewage lagoons.

Seaweed and Freshwater Algal Culture

Distribution and Yields--

Freshwater algae grows in waterbodies throughout the country. Marine algae is found in coastal environments. Algal productivity tends to be higher in more southern latitudes.(48)

Most of the research in algal productivity has been in mass culturing experiments. Yields reach 169 metric tons (dry weight biomass)/hectare/year (75 tons/acre/yr).(49)

Algal yields in freshwater exceed those of marine environments. Goldman, Ryther, and Williams(48) indicate that yields 10-20 g (dry wt biomass)/m^2/day (0.002-0.004 lb/ft^2/day) have been reported for freshwater algae in Europe. On an extrapolated basis this is the equivalent of 36.5-72.5 metric tons/ha/year (16.2-32.3 tons/acre/yr). The same authors review that 5-12 g (dry weight biomass) (0.01-0.03 lb) has been attained in marine mass cultures. This equates to about 18 metric tons/hectare/yr (8.2 tons/acre/yr) for the lower value assuming sustained yields are possible.

Detailed chemical compositions for freshwater algae have not been located. Algae is well known for its high protein content. Table 19 shows composition for the giant California kelp, Macrocystis pyrifera.(50) The kelp is about 88 percent water.

Cultivation, Harvest, and Storage--

Turnover rate of new fronds is about 6 months. Propagation can be achieved by experimental manipulations.

Rafts of rope networks serve as substrate for kelp plants in some experimental facilities in southern California waters. The raft covers about 3 hectares (7.4 acres) and is anchored 9 meters (30 ft) below the ocean surface. Once successful, ocean energy farms could be much larger.

The common red seaweed, Eucheuma isiforme, is being grown experimentally as a source of chemical colloids. Harvesting methods at the present are by hand in natural populations and occur at the rate of 4,000 metric tons per year (4408 tons).(52) Marine farms could support about 1,100 plants/hectare. Each hectare could yield 300-500 wet metric tons of harvested organic matter/year.(50) The cultures would do best in upwelling areas.

Harvest and storage regimes are being worked out.(50)

TABLE 19. COMPOSITION OF THE GIANT CALIFORNIA KELP

Component	Percent of Dry Weight
Ash (45)	
KCl	29
NaCl	7
Na_2SO_4	4
Ca, Mg	4
Volatile Solids (55)	
Carbohydrates	<64
Proteins and Fats	ca. 10

Projections of Current Trends and Recommendations--

Mariculture as a biomass source for fuels merits consideration. In principle, the high productivity and vast cultivation area potential would seem ideal. However, the embryotic level of cultivation and certain engineering developments as well as unusual susceptibility to adverse weather conditions, suggest this biomass source will be one of the last developed.

The literature on aquaculture is vast. A closer look at this literature is needed before projections can be made. One of the problems with small body sizes is the reduced volumes of material for handling. Another is the energy subsidy needed to maintain the growth in the log phase. Dykyjova(52) has shown that emergent marsh plants (see Marsh Plants) are more productive than cultures of uni-cellular algae under similar climatic conditions. However, algae can be grown in conditions not conducive to growth of marsh plants. Szetella, Krascella, and Blecher(53) detail many other aspects of mariculture farming and fuel production.

ENERGY CROPS

Initial Screening

Energy crops are those crops grown especially for their potential as sources of energy. Some of the important criteria for recognizing a good energy crop include the following:

- High net ecological productivity
- Easy cultivation of large acreages
- Sound genetic stock for resistance to disease and pests.

Several crops meet these criteria. They include sugarcane and sugar beets.

Sugarcane

Distributions and Yields--

Sugarcane (Saccharum afficinarum) is grown in Florida, Louisiana, Texas, Hawaii, and Puerto Rico. The approximate areas are provided in Table 20. In Florida sugarcane is being grown in three counties peripheral to Lake Okeechobe.(54) South central Louisiana is the principal growing area in Louisiana, with small acreages in central Louisiana.(55) Four of the Hawaiian Islands have sugarcane; almost one-half of the cultivation occurs on the Island of Hawaii.

Yields of cane are expressed in various ways. Generally, only the above-ground portion actually utilized for sugar production is considered. When yields are given as total biomass, the sugar producing stalks constitute about 70 percent and the tops, root system, and soil approximately 30 percent. Yield is also a function of geographical location and cultural practices. For example, the ratoon system produces 4 harvests in 5 years. In Florida and Louisiana yields average 105 metric tons biomass/hectare (wet weight) (47 tons/acre). Wet weight yields range from 155 to 185 metric tons/hectare (69-83 tons/acre) for certain varieties. Experimental

TABLE 20. GEOGRAPHIC LOCATIONS AND AREAS OF SUGARCANE CULTIVATION IN THE UNITED STATES(24)

Location	Area Hectares	Acres
Florida	107,000	272,000
Louisiana	130,000	331,000
Texas	14,000	35,700
Hawaii	40,000	101,000
Puerto Rico	53,000	132,000

varieties and conditions have produced even higher yields. Assuming 30 percent dry matter, then average dry weight yield is about 30-35 metric tons/hectare/year (13-16 tons/acre/yr).

Chemical composition of sugarcane is shown in Table 21. Note that water content is about 70 percent. Ash content for sun-cured sugarcane (aerial part) is about 4 percent.

Ecological limitations on sugarcane production are temperature and availability of soil moisture. Sugarcane is susceptible to freezing. Soil temperature must attain 21 C (70 F) to start the growing season. Sugarcane needs adequate rainfall. Also, pests such as rats, sugarcane borer, and certain weeds are problems. Management limitations include milling facilities and planting methods. It is thought that sugarcane production could be improved by harvesting annually in Florida and other mainland states.

Current uses of sugarcane are principally for the production of cane sugar. Of course, some of the land is devoted to seed production. Bagasse and other cane residues are used for soil amendments, papermaking, bedding for animals, and wallboard.(56)

TABLE 21. COMPOSITION OF SUGARCANE

Component	Mean Percent of Wet Weight
Dry Matter	24-27
Fiber	11-16
Soluble Solids	10-16

Cultivation, Harvest, and Storage--

Nearly all phases of sugarcane farming are mechanized. Several experimental stations research new varieties; the practice and development of sugarcane farming is an active area.

Fields in Hawaii are planted and harvested continuously. In Florida and Louisiana the ratoon system is used; this harvest system depends on growth from root stocks for 5 years with 4 harvests. Experimental work should show that, by reducing the distance between row spacing or by broadcast planting, production of biomass can be greatly increased.

After harvesting in the field, sugarcane can be attacked by fungi. Usually the cane is processed rapidly enough that deterioration is not a problem.

Projections of Current Trends and Recommendations--

There is essentially no more land into which to expand sugarcane production in Hawaii, so expansion in the United States will be limited to the south southern regions of the continental U.S. Sugarcane has been reintroduced into Texas in the last few years and its area there is expected to increase. Presumably, sugarcane could be grown in other southern states.

Sugarcane is one of the most productive crops in the world. Genetic and breeding programs could accelerate the identification of varieties whose biomass yields are even greater. Different management practices can also improve the yield.

Sugar Beets

Distribution and Yields--

Sugar beets have been grown in the western and midwestern United States for many years. Not only has sugar and beet pulp for cattle been processed from the root, but after harvest the leaves or tops have been grazed by cattle and ensiled for animal feed. Although sugar beets are cultivated in 17 states, about 81 percent are grown in 8 states; Table 22 shows the hectarage for 1975.(57)

Productivity of sugar beets expressed as metric tons (wet weight)/hectare/year ranges from 25 to 61 (11-27 tons/acre/yr).(57) The following highest average yields for the period 1973-75 are: Washington; 58 metric tons/hectare/yr (26 tons/acre/yr), and California; 57 metric tons/hectare/yr (25 tons/acre/yr).(57) In general, an average annual yield of about 43 metric tons is considered a good crop. Assuming dry weight to be 20 percent of wet weight and tops to be about 15 percent of total plant biomass, the average productivity of the sugar beet is about 10 metric tons (dry weight)/hectare/year (4 tons/acre/yr). Since about 614,000 hectares (1,520,000 acres) were in beet cultivation in 1975, there were about 21,000,000 metric tons (23,000,000 tons) of sugar beets produced in that year.

Biological and management limitations to sugar beet production are numerous. The best soil conditions are deep, well-drained and loamy.(58) Acid soils of pH 5-5.5 and below are not favorable. Nitrogen is often needed as a fertilizer.(59) Nematodes are the major pest and crop rotation is a must to regulate this worm. In certain areas of the west, sugar beet production has ceased because of high nematode infestations.

Sugar beets are utilized as a major source of raw sugar in the United States. Pulp from the roots is used as a food additive for cattle production. Tops are used for feed to animals.

Cultivation, Harvest, and Storage--

Sugar beet technology is well advanced. Most all phases of sugar beet production and processing are mechanized. Pest management systems have been developed. Harvesting machines have gone through several generations of design.

TABLE 22. GEOGRAPHIC LOCATIONS AND AREAS OF SUGAR BEET CULTIVATION IN THE UNITED STATES

Locale	Area Hectares	 Acres
California	132,000	326,168
Minnesota	79,000	195,206
Idaho	64,000	158,142
Colorado	63,000	155,671
North Dakota	53,000	130,961
Nebraska	39,000	96,368
Michigan	37,000	91,426
Washington	33,000	81,542

Projections of Current Trends and Recommendations--

Demand for sugar will probably increase and thus areas of cultivated sugar beets will also increase. Sugar beets can be grown in many parts of the country where they are not currently being cultivated. The technologies of sugar beet production, processing, harvesting and storage are well advanced. The recycle of waste products is so extensive that little, if any, energy could be recovered from this resource.

SILVICULTURAL PRODUCTION

Initial Screening

A literature survey was initiated to select those tree species which appeared to have potential for biomass production on a large scale. The criteria for selection of these species were high productivity (rapid growth), ease of establishment, vigorous regeneration, and wide geographical distributions covering large areas of the U.S. capable of supporting trees. A list of the tree species evaluated is given in Table 23.

Potential Silvicultural Species

The species of trees initially selected as having greatest potential for commercial production of biomass are all hardwoods (Table 24). These species are rapid growing, are easily planted and sprout vigorously from stumps and are generally pioneer or subclimax successional species. Several of the species (e.g., sycamore) are grown commercially in plantations and data are readily available on production, but some (e.g., tree of heaven) have not been studied extensively and information is sparse.

Distributions, Yields, and Characteristics--

The tree species under consideration (Table 24) for which data are available have similar chemical characteristics. Oven dry weight is approximately 50 to 60 percent of wet weight, ash content is 1 to 2 percent of dry weight and cellulose content is approximately 35 to 40 percent except for *Eucalyptus* which may be 8 to 10 percent higher.(28) Energy content for trees (including foliage, branches and bole) ranges 4500-5000 kcal/kg (8100-9000 Btu/lb). Above ground biomass yields of selected tree species are presented in Table 24.

Poplars (*Populus* spp.) and cottonwoods have the widest distributions of the trees selected. Eastern cottonwood is (*P. deltoides*) found in eastern North America from Quebec and southern Ontario west to North Dakota, south to southern Texas and northern Florida; it is absent in the higher elevations. Best growth occurs in alluvial bottomlands of the Mississippi River and its tributaries from Missouri to Louisiana. Black cottonwood (*P. trichocarpa*) is found in the Pacific Northwest forests from southeast Alaska to the mountains in southern California; its range extends eastward to Montana, central Idaho and northern Utah and Nevada. The largest trees are found in moist areas at low elevations. Cottonwoods exhibit rapid growth of up to 2.5 cm (1 in.) and 1.5-2.4 m (5-8 ft) in diameter and height, respectively, per year.(65) They sprout vigorously from stumps and are thus good for coppicing, e.g., regeneration from stumps. Cottonwoods are intolerant of shade and require moist soil.(66) Other poplar species which may be good prospects for intensive management are Lombardy poplar (*P. nigra* var. *italica*), an introduction from Europe and used extensively for windbreaks and as ornamentals, and poplar hybrids. Lombardy poplars have been planted extensively in the western U.S. and do not appear to require as moist conditions as cottonwoods. Various hybrids are being experimentally developed to obtain fast growing and hardy trees.

Sycamore (*Platanus occidentalis*) is another rapid-growing tree common in the eastern U.S. It is found east of the Great Plains, south to Texas and Georgia, and north to the Great Lakes and New England. It is limited in the north by cold temperatures and in the west by insufficient moisture. In natural stands, its growth is exceeded only by cottonwoods and sometimes a few pines, soft maple and black willow.(65) Sycamore is easy to establish in plantations and sprouts quickly from stumps after coppicing. It is

TABLE 23. TREE SPECIES CONSIDERED FOR SILVICULTURAL PRODUCTION

Common Name	Scientific Name
Alder, European(a)	*Alnus glutinosa*
Alder, red(a)	*Alnus rubra*
Ash, white	*Fraxinus americana*
Basswood	*Tilia* spp.
Birch, gray	*Betula populifolia*
Birch, river	*Betula nigra*
Cherry, pin	*Prunus pennsylvanica*
Cottonwood, eastern(a)	*Populus deltoides*
Cottonwood, black(a)	*Populus trichocarpa*
Eucalypts(a)	*Eucalyptus* spp.
Fir, Balsam	*Abies balsamae*
Fir, Douglas	*Pseudotsuga menziesii*
Fir, white	*Abies concolor*
Larch, western	*Larix occidentalis*
Locust, black	*Robinia pseudoacacia*
Maple, bigleaf	*Acer macrophylum*
Maple, red	*Acer rubrum*
Maple, silver(a)	*Acer saccharanium*
Mountain-ash	*Sorbus americana*
Oak, black	*Querqus velutina*
Oak, live	*Querqus virginiana*
Oak, red	*Querque rubra*
Pine, loblolly	*Pinus taeda*
Pine, longleaf	*Pinus palustris*
Pine, slash	*Pinus elliottii*
Pine, white, eastern	*Pinus strobus*
Pine, white, western	*Pinus monticola*
Poplar, hybrid(a)	*Populus*

TABLE 23. (continued)

Common Name	Scientific Name
Poplar, Lombardy[a]	*Populus nigra* var. *italica*
Redcedar, western	*Thuja plicata*
Sassafras	*Sassafras albidum*
Spruce, blue	*Picea pungens*
Spruce, Sitka	*Picea sitchensis*
Sweetgum	*Liquidambar styraciflua*
Sycamore[a]	*Platanus occidentalia*
Tree of heaven (Ailanthus)[a]	*Ailanthus altissima*
Yellow poplar (Tuliptree)[a]	*Liriodendron tulipifera*

(a) Tree species deemed as having highest potential for silvicultural production of biomass, based on ease of establishment, growth rate, regeneration and distribution.

TABLE 24. ABOVE GROUND BIOMASS YIELDS OF SELECTED TREE SPECIES

Name	Location	Growth	Yield (dry wt.) Mt/ha/yr (ton/ac/yr)	Source
Eastern cottonwood	Louisiana	Seedling	3.8-12.1 (1.6-5.4)	60
Black cottonwood	Washington	—	10.1 (4.5)	28
	Washington	Seedling	9.2 (4.1)	60
		Coppice	2.2-13.4 (1.0-6.0)	60
Hybrid poplars	Pennsylvania	Seedling	9.0 (4)	28
		Coppice	17.9 (8)	28
Sycamore	Georgia	Seedling	0.4-37.0 (0.2-16.5)	61
		Coppice	6.7-9.0 (3.0-4.0)	
Red alder	Oregon	Seedling	13.2-22.2 (5.9-9.9)	62
	Washington	—	22.4 (10)	28
	Washington; British Columbia	Seedling	4.5-56.0 (20-25.0)	60
Eucalyptus spp.	California	—	34.5-62.0 (15.4-27.7)	28
Yellow poplar forest *	—	Seedling	24.1 (10.8)	63
Temperate deciduous forest*	—	Seedling	12.0 (5.4)	64

* Forest includes trees and understory.

very shade intolerant and requires the use of herbicides for seedlings to survive. Seedling growth is rapid, up to 1.5 m (5 ft) the season after planting.(61) Moist soil is required for optimum growth.

Red alder (*Alnus rubra*) is a very rapid growing tree found along the Pacific coast from southeast Alaska to southern California. It is usually within 160 km (99 mi) of the coast and below 760 m (2500 ft) elevation. Best growth is below 460 m (1500 ft). Red alder requires humid to superhumid conditions with at least 635 mm (25 in) of precipitation annually(65); consequently its range is quite limited by its habitat requirements. It is very intolerant of shade(66) and easily damaged by fire. Stands are sometimes defoliated by tent caterpillars.(67) Red alder is one of the most important timber trees in the Northwest.(65) Alders are a pioneer species and are important in the ecosystem for their ability to fix nitrogen and thus increase the soil fertility. Because of this ability, alders are often planted in disturbed areas and are able to survive where other species cannot. During a 20-year rotation, red alder may increase soil fertility by the addition of nearly 165 metric tons per hectare (74 tons per acre) of nitrogen.(62) European alder (*A. glutinosa*) has been planted on strip-mined lands. Yields on strip-mined lands will be reduced by the low soil fertility and will be affected by the available soil moisture, but site protection and improvement would result along with the production of wood fiber.(68)

Eucalyptus spp. are among the fastest growing trees in the world. They are natives of Australia and New Zealand but have been introduced into many parts of the world. They are currently grown in California and Hawaii. *Eucalyptus robusta* is the most abundant hardwood in Hawaii.(69) *E. globulus* is one of the more common species in California. Eucalypts are very fire sensitive and may be susceptible to frost. It is pest resistant and sprouts profusely from stumps, lending itself to short rotations. Eucalypts produce dense wood, have a high cellulose content and low water content (about 40 to 45 percent). *E. globulus* grows best in well-drained soils with ample moisture but is tolerant of poor shallow soils. Seedlings of *E. globulus* may reach 18.3 m (60 ft) in nine years.(28) Sources of detailed information on eucalypts grown in the U.S. have not been identified.

Yellow poplar (= tuliptree, *Liriodendron tulipifera*) is a rapid growing tree of the eastern U.S. It is found west to Michigan, south to central Florida, and north to southern New England. It requires moist, well-drained soils and is intolerant of shade. Annual diameter growth may be 0.8 cm (1/3 in.).(65) Seedlings are difficult to transplant, but stumps sprout vigorously. Because this species is usually considered together with other hardwoods, specific information is not readily available.

Soft maples, particularly silver maple (*Acer saccharinum*), are rapid growing trees. Silver maple is found in the eastern U.S. west to Minnesota, south to Florida and Louisiana. It is absent in the higher elevations and along the Atlantic coast. It is a bottomland species, requiring good soil moisture. Stumps sprout vigorously and stems may grow 1.3 cm (0.5 in.) in diameter annually.(65) It is not tolerant of shade.(66) Specific information on growth rates is lacking as it is generally classified with other forest species.

The tree of heaven (Ailanthus altissima) is a very rapid growing species introduced from Eastern Asia. It is used as an ornamental but has escaped and become naturalized in the eastern U.S.(67) It is a very hardy species, growing well in hard packed soils.(66) It sprouts vigorously from stumps and may grow as much as 2.5 cm (1 in.) a day. It has been reported to grow 3.6 m (12 ft) in a season.(67) The flowers have a very noxious odor. Because it is not considered of commercial importance as a tree and is planted as an ornamental, data on growth, yield, and air pollution characteristics are very sparse.

Cultivation, Harvest, and Storage

It is widely held(28,60,70) that intensive management practices, such as those currently used in agriculture to produce large amounts of food and fiber, can be applied to various tree species to produce large amounts of biomass for conversion into energy. Such management practices for energy plantations are still in the initial stages of development and definitive silviculture techniques for the tree species likely to be used for plantations have not been established. However, based on experience with intensively cultivated agricultural species and research with tree species such as sycamore, a generalized management scheme, including cultivation, harvesting, and storage techniques, can be envisioned for energy plantations using the hardwood species having potential as an energy crop.

Cultivation techniques begin with the selection and preparation of the energy plantation site. As with any crop, the best sites are those with relatively flat, fertile land and good moisture availability.(28) Energy plantations will have to compete with agricultural and other uses (subdevelopments, urban expansion, etc.) of this land. The decision governing land use will be strongly influenced by the economics of the various competing uses. Marginal lands represent another kind of site that have potential for energy plantations. These lands include those that have been surface mined, those with infertile soils and steep slopes, and others with deficiencies that make them unsuited to agriculture. Energy plantations on such land will be less productive than those with better soil, slope, and moisture conditions. At the same time, tree crops on these lands will often result in considerably higher productivity than would be realized under natural, unmanaged conditions and will offer potential for reclamation and improvement of these marginal lands.

Upon selection of the site for the energy plantation, the land must be prepared for planting. This involves clearing and tilling, followed by treatment with herbicide and fertilizer.(28,61) Herbicide treatment will reduce competition by weeds for valuable nutrients. The fertilizer will augment the natural soil nutrients and act to increase productivity. The ratio of nitrogen, phosphorous, and potash will vary according to soil characteristics and species to be planted.

The prepared land will be planted with the tree species of choice. Most plantings will involve the use of seedlings reared in a nursery. The spacing of the seedlings is important. The seedlings must be placed close enough to result in a dense stand of trees that intercepts most of the incident sunlight and grows rapidly to provide a large amount of biomass per hectare. Too close spacing results in competition among seedlings for light and nutrients and reduced growth and productivity. Experiments with seedling spacing have indicated that 1 x 4 (seedlings in each row spaced 1 foot [0.3 meters] apart; rows are 4 feet [1.2 meters] apart) or 2 x 4 are most productive for energy crops.(28) Trees for energy can be spaced considerably closer than trees for timber. Some experimental work done with vegetative propagation results in considerably less effort and cost than seedling transplants of sycamore.(61) Stems of sycamore from 0.3 to 1.2 meters (1-4 feet) long were placed horizontally in furrows and covered with 8 to 15 cm (0.3-0.5 feet) of soil. The buds on the buried stems produced new plants. Because most of the hardwood species considered for energy plantations can reproduce from coppice or root stalk (the alders), only a single planting will be necessary to produce multiple short rotation crops.

Cultivation practices after the planting of the tree crop may include treatment with pesticides and fertilizer and irrigation. The frequency and kind of application will depend on the location of the plantation and the species grown. In most cases, one application of herbicide during the first year of growth will be sufficient for weed control. The shading by the dense canopy in later years will act to reduce weeds. Insecticides and fungicides will likely be needed periodically throughout the rotation period. Application of pesticides of all types after the first year of growth will probably have to be done by aircraft. The dense stands will prevent the effective use of ground-based application techniques.(28)

Irrigation may be necessary since most of the tree species do require significant quantities of moisture for high productivity. Irrigation may be particularly needed for plantations on marginal soils or where natural precipitation is low or out of synchrony with the growing season.

Fertilization will be needed if high yields are to be obtained. The amounts and kinds of fertilizer will depend on the natural fertility and other important characteristics of the soil and the tree species that is being grown. In addition to nitrogen, phosphorus, and potassium normally required, other additives, such as lime in acid soils (especially on surface mined lands), may be required to achieve high growth rates. Commercially available fertilizers as well as sewage are likely sources of these nutrients. The treatment of land with liquid sewage merits special consideration in areas where it is readily available--primarily near large urban centers.(70) Sewage is nutrient rich and the spreading of this material on land as an ameliorant rather than discharging it to a river or lake shows much promise in reducing the costs of fertilizing as well as the costs for further sewage treatment and disposal.

It is envisioned that all of the aspects of cultivation, from the initial preparation of the site through water, fertilizer, and pesticide application will be highly mechanized and that labor requirements would be comparatively small.

Harvesting procedures for tree plantations are based on a short rotation time of 2 to 6 years.(28,60,70) The fastest growing species (*Eucalyptus* and alder) may be cropped every 2 years on good sites. Slower growing species and plantations on poor quality sites should be harvested at longer intervals, up to 6 years. The timing of the harvest during the year will depend on several factors. The above ground portions of the trees can be taken at any season without endangering the regenerative ability of the stumps or roots.(60) However, cropping in mid summer (August) may result in frost damage to the new buds in the fall of the year and consequently slow the growth rate of the succeeding crop. Another influencing factor is the operating schedule of the processing plant. In most cases, it is advantageous to convert the biomass to energy relatively soon after harvest to eliminate the need for costly storage facilities and prevent potential degradation of the crop by pests and other causes. Ideally, the harvest should be at a time that will permit processing quickly. In cases where several different kinds of biomass are processed by a single facility, the timing of the harvest should coincide as much as possible with the time when the facility can best process the material. Short-term storage may be required in many cases. A third factor influencing the time of harvest is the overall objectives of the energy plantation. If energy yield is the only objective, harvesting the energy rich foliage, as well as the stems and boles, during the early fall may be best. If management objectives include reclamation of marginal or disturbed lands or a reduction of intensity of fertilization, then harvesting after leaf fall would be desirable. The leaves would be permitted to fall to the soil where decomposition would replace some of the nutrients taken up by tree growth and reduce the amount of fertilizer needed to maintain high growth rates. Dormant season harvesting would also reduce the net yield of the energy crop.

In terms of timing of the harvest, the energy plantation would be designed to have a staggered rotation sequence so that a fraction of the crop would be available for harvest each year. For 2- to 6-year short rotation crops, one-half to one-sixth of the total crop would be ready for harvest each year. This will even out the material available for the processing facility.

As with cultivation, harvesting will be highly mechanized. A silage-type harvester taking all the above ground material would be used.(28) The harvested material would be fed to a chipper where it would be reduced to small chips. This material would be transported by truck to a nearby drying area where it would be air dried for several days. Additional equipment would be required to turn the wood chips periodically to insure complete air drying. In very humid climates a more rigorous drying procedure using indirect heat sources may be necessary.

Storage is the final consideration in the management of tree biomass for energy conversion. Because the availability of tree biomass and the feedstock demands of the conversion facility are not likely to be well synchronized, storage of the feedstock at least for short periods of time (a few months) will likely be required. Of the possible biomass sources, tree biomass is among those better suited for storage. Chipped wood stored in large piles is relatively resistant to pest and chemical degradation. The interior of these piles should be nearly anaerobic and cellulose and related compounds comprising wood are not easily or quickly decomposed. Storage areas may be located on the energy plantation or at the conversion plant. If considerable distance separates the two, storage at the conversion facility may be most desirable insuring a supply of biomass feedstock whenever it is needed.

The ultimate factor determining if energy plantations using trees will be competitive with other uses of the land (agriculture, recreation, urban development) is economics. While economic analysis is beyond the scope of this program, it is possible to at least estimate the energy costs associated with the silviculture practices. Dollar costs can then be assigned to the energy costs. However, inflation, changing supplies and demands, and shifting local, state, national, and societal needs make dollar costs virtually impossible to fix, especially for a new, untried energy source such as biomass. Thus, the analysis presented here will be limited to energy costs in kcal per hectare-yr.

Table 25 summarizes the energy consumption estimates for an intensively managed 4-year short rotation energy plantation (data modified slightly from Alich and Inman).(28) It indicates that for every kcal consumed in farming or production of farm equipment and materials, more than 5 kcal can be harvested in the tree crop. Rose(70) reported ratios of 1:6.48 to 1:8.44 but assumed somewhat more biomass production per hectare.

It must be emphasized that these energy estimates are generalized figures which would be produced per hectare-year. Tree plantations, while less productive than some of the grasses, can produce considerable energy for long periods of time. Only a thorough economic analysis can determine if such plantations can compete with other uses of the land.

Projections of Current Trends and Recommendations

The use of tree plantations as a renewable energy resource constitutes a new and competitive use of land in the U.S. The prime competitors are agriculture, silviculture for sawtimber and pulp, and urban development. At present, economics likely place energy crops at a disadvantage with these other uses. However, as nonrenewable fossil fuel reserves are depleted and demands for energy continue to grow, renewable sources of energy will become a more important and competitive use of high quality, fertile land.

Recent trends in land use in the U.S. have shown a drop in the amount of land in intensive agriculture(71) and silviculture.(60) This reduction is likely the result of two causes: (1) the use of land for other developments, especially urban and suburban expansion, and (2) the cessation of these intensive activities on marginal lands of low productivity. These trends are likely to continue in the near future. The human population in the U.S. will continue to grow requiring more living space. New developments in intensive cultivation techniques as well as new, highly productive varieties of trees and other crops will continue to improve the productivity per hectare on fertile land and make marginal land even more unsuitable for intensive cultivation (it is uneconomical to use intensive, expensive farming methods on land whose best yields can only be a small fraction of those having more fertile soils).

TABLE 25. ENERGY CONSUMED IN AN INTENSIVELY MANAGED TREE CROP ENERGY PLANTATION

Management Operation	kcal/ha-yr Consumed	Btu/acre-yr Consumed
Farming operations		
Field tasks	750,072	1,204,655
Irrigation	1,222,025	1,962,636
Miscellaneous	31,741	50,978
Farm chemicals manufacture	6,977,852	11,206,793
Farm machinery manufacture	255,485	410,322
Seed production	27,712	44,507
Total energy consumption	9,264,887	14,879,890
Total energy yield (11.2 metric tons at 3.4 x 10^6 kcal/ton)	46,500,000	74,681,416
Energy balance	37,235,113	59,801,526
Energy input : energy output	1:5.0	1:5.0

Source: Alich and Inman.(28) Data modified slightly and converted to metric units.

These patterns in land use reveal that marginal lands offer immediate opportunities for the development of energy crops. Of all the energy crops, trees have the most potential for efficient productivity on such lands. While trees are less productive than many other energy crops, they also require less intensive management and can provide good, if not outstanding, yields on moderate energy, labor, and capital inputs. In addition, tree species, especially nitrogen fixers such as the alders, can assist under proper management techniques to reclaim marginal lands by enriching the soil and reducing erosion as well as provide an energy crop.(68) For surface mined lands where reclamation is desirable or required, a shift in management objectives and the species used for reclamation could result in the establishment of energy plantations with little additional research, labor, machinery, and capital.

In the future, as demands for renewable energy sources increase, large energy plantations ($\sim$ 40,000 hectares)(28) will become feasible. In the warmer climates of the U.S., the prime energy crops will be sugarcane and other species. Smaller amounts of land will be planted in trees to augment production during the cool months of the year. In cooler temperate and northern climates, trees may take a more important role in energy plantations. Many of the techniques now used in food and fiber crops will need to be utilized for tree species if tree productivity is to be maximized. Highly productive and disease, draught, and pest resistant varieties and hybrids will need to be developed, as will efficient planting, cultivation, harvest, and storage techniques. With the development of appropriate tree varieties and corresponding management techniques, energy plantations using trees will be a competitive alternative use of both marginal and fertile lands of the U.S.

INDUSTRIAL AND URBAN WASTES

Screening of Materials

Sources of industrial and urban solid wastes number in the hundreds, and include food and kindred product industries, slaughtering of animals, textile mills, chemical plants, rubber and plastic products, explosives, and insecticides, and even waste treatment plants. The multiplicity of sources and the nature of the wastes have resulted in various differing estimates of the national industrial and urban waste flow. These estimates are based on the inclusion and/or exclusion of various materials, and on the use of information at various points in time; often the assumptions are not clearly shown with the estimates. However, the estimates vary in minor ways rather than by orders of magnitude. Another important consideration, not always possible to evaluate in the data, revolves on the inability to distinguish organic and inorganic materials. Information from various perspectives will be provided because of the complexity of obtaining and interpreting data on industrial and urban wastes.

Because of the multiplicity of studies of solid and industrial wastes, the post and current commitment of EPA and others to this biomass source, and the broader objectives of this study, a decision was made early in this work to de-emphasize this category.

It should not be implied that this decision suggests this source as unimportant; rather, it is a recognition of the existence of an already comprehensive body of knowledge, in this area, and the need to begin developing a complimentary data base in other biomass sources.

Kinds of Materials

The majority of the organic portion of solid waste mix is associated with paper, food, and yard materials (Table 26). Inorganic composition includes glass, metals, and plastics. The ratio of organic to inorganic municipal wastes seems to be about 4 to 1 according to Niessen and Chansky.(72)

TABLE 26. AVERAGE PERCENT COMPOSITION OF MUNICIPAL SOLID WASTE(72)

Organic Material	Percent	Inorganic Material	Percent
Paper	35.8	Glass	8.4
Food waste	18.7	Metal	8.2
Yard waste	20.4	Plastics	1.3
Leather, rubber	1.4	Dirt	1.6
Wood	2.3	Total	19.5
Textiles	1.9		
Total	80.5		

Distribution and Quantities

Figure 2 provides an overview of the urban waste stream in the United States for 1973.(73) Note that over one-half of the 273 x 10^6 metric tons/yr (300 x 10^6 tons/yr) is being used or is usable in processing plants. Of 145 x 10^6 metric tons/yr (160 x 10^6 tons/yr) of municipal solid waste, about 118 x 10^6 metric tons/yr (130 x 10^6 tons/yr) could be diverted to processing systems. The other 27 x 10^6 metric tons/yr (30 x 10^6 tons/yr) is currently being incinerated (some for generation of electricity) and being placed in landfills or dumped in some other way. The flow--not suitable for processing plants--contains fly ash, junk autos, appliances, rocks, and similar materials.

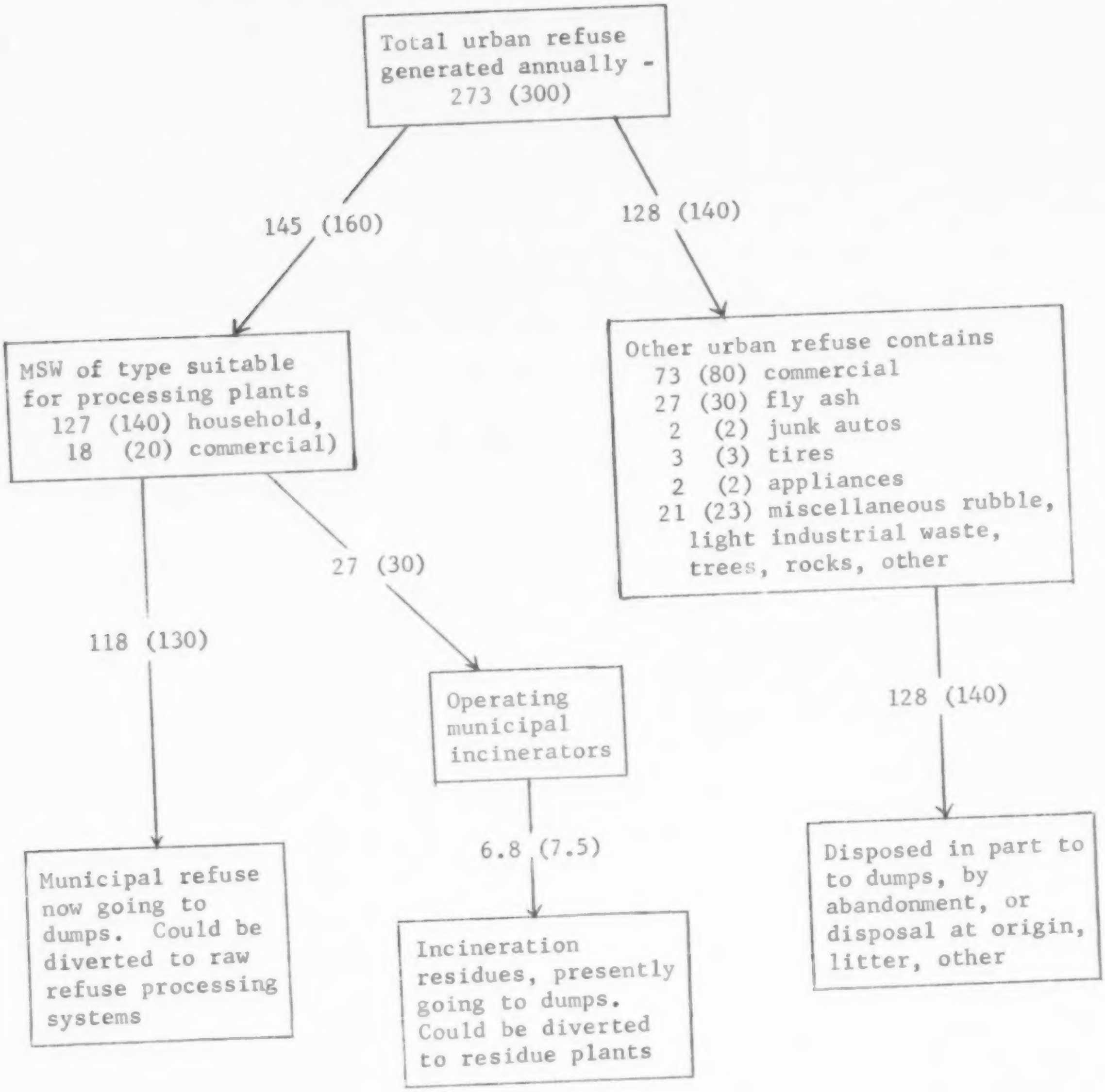

Total urban refuse generated annually - 273 (300)
145 (160)
128 (140)
MSW of type suitable for processing plants
127 (140) household,
18 (20) commercial)
Other urban refuse contains
73 (80) commercial
27 (30) fly ash
2 (2) junk autos
3 (3) tires
2 (2) appliances
21 (23) miscellaneous rubble, light industrial waste, trees, rocks, other
27 (30)
118 (130)
128 (140)
Operating municipal incinerators
6.8 (7.5)
Municipal refuse now going to dumps. Could be diverted to raw refuse processing systems
Incineration residues, presently going to dumps. Could be diverted to residue plants
Disposed in part to to dumps, by abandonment, or disposal at origin, litter, other

Figure 2. An overview of the urban waste stream in the United States for 1973.(73) [Units are 10^6 metric tons/year (10^6 tons/year)]

The quantitative flow of organic wastes from industrial and urban sources was estimated as being 213 x 10^6 metric tons/yr (235 x 10^6 tons/yr) in 1971.(74) The estimates include four categories of organic wastes: urban refuse (117 x 10^6 metric tons/yr); industrial wastes (40 x 10^6 metric tons); miscellaneous organic wastes (45 x 10^6 metric tons/yr); and municipal sewage solids (11 x 10^6 metric tons/yr). Table 27 shows these amounts and further indicates that a larger proportion of urban refuse is being collected than other categories. Thus, industrial wastes, miscellaneous organic wastes, and municipal sewage solids are a potential target for collection.

TABLE 27. CATEGORIES OF ORGANIC WASTE WITH THEIR PATTERNS OF GENERATION AND COLLECTION(74) IN THE UNITED STATES FOR 1971

Category	Status Generated *	 Collected *	Portion Collected (%)
Primary			
Urban refuse	117 (129)	64 (71.0)	55
Industrial wastes	40 (44)	4.7 (5.2)	12
Miscellaneous organic wastes	45 (50)	4.5 (5.0)	10
Secondary			
Municipal sewage solids	11 (12)	1.4 (1.5)	13
Totals	213 (235)	75.0 (82.7)	

*Units are 10^6 metric tons/yr (10^6 tons/yr).

Net solid wastes for 1971 and 1973 averaged about 118,000,000 metric tons/yr (130,000,000 tons) (Table 28).(75) Combined paper and food wastes represent about 55.5 x 10^6 metric tons/yr (61.1 x 10^6 tons/yr) (1971) and (60.4 x 10^6 tons/yr) (1973) of the total 113.2 x 10^6 (124.8 x 10^6) and 122.3 x 10^6 (134.8 x 10^6), respectively. Paper and food wastes in 1973 represent 49 percent of the total net weight of these types of urban/industrial waste (Table 28). Paper wastes increased about 13 percent between the two years; thus, paper represents a growing organic source of waste.

Recent studies of the residential-commercial components of municipal solid waste equated to 1.5 Kg (3.3 lbs) per capita per day in 1971.(75) The estimates for 1976 are 1.6 Kg (3.6 lb) per capita per day.(75)

TABLE 28. NET SOLID WASTE (WET WEIGHT) BY MAJOR CATEGORIES IN THE UNITED STATES FOR 1971 AND 1973(75)

Material Composition	1971*		1973*		Growth, 1971-1973		
					Weight*		Percent Change
Paper	35.5	(39.1)	40.1	(44.2)	4.6	(5.1)	13.0
Glass	10.9	(12.0)	12.0	(13.2)	1.1	(1.2)	10.0
Metal	10.7	(11.8)	11.3	(12.5)	0.6	(0.7)	5.9
Plastics	3.8	(4.2)	4.5	(5.0)	0.7	(0.8)	19.0
Rubber & Leather	3.0	(3.3)	3.3	(3.6)	0.3	(0.3)	9.0
Textiles	1.6	(1.8)	1.7	(1.9)	0.1	(0.1)	5.5
Wood	4.2	(4.6)	4.5	(4.9)	0.3	(0.3)	6.5
Subtotal: Non-food products	69.8	(76.9)	77.5	(85.4)	7.7	(8.5)	11.1
Food Waste	20.0	(22.0)	20.3	(22.4)	0.4	(0.4)	1.8
Subtotal: Product waste	89.7	(98.9)	97.8	(107.8)	8.1	(8.9)	9.0
Yard Waste	21.9	(24.1)	22.7	(25.0)	0.8	(0.9)	3.7
Miscellaneous Inorganics	1.6	(1.8)	1.7	(1.9)	0.1	(0.1)	5.6
Total Material	113.2	(124.8)	122.3	(134.8)	9.1	(10.0)	8.0

*Units are 10^6 metric tons/yr (10^6 tons/yr).

Of course, the larger the population of a city, the larger the solid waste stream. Indeed, the amount of municipal solid waste from the residential-commercial sector of any city could be estimated by multiplying the per capita rate by the population. This approach would be useful for a national perspective. Regional and certainly smaller geographical units (counties) will require more specific information for planning purposes.

At least three toxic materials are important in urban waste: metals, pathogens, and disease vectors. Metals include tin, lead, sulfur, iron, zinc, and mercury. Pathogens include viruses, bacteria, cestodes, and dipteran larvae. Direct and indirect vector transmission of disease is possible via rats, fleas, sick animals, and pests that feed on or live in garbage and refuse.

One of the major limitations is the dispersed nature of the wastes. It is often not profitable to collect the material. Also, the material is often of diverse composition and must be processed and/or separated before usable fractions are available. Separation of inorganics from organics can present a technological problem.

The technology of using urban wastes is sophisticated in many places. Recycling plants and production systems that generate electricity by burning municipal wastes are growing in number. A third use category is landfills. Many studies of waste-to-energy projects exist; one list is found in a paper by Klass.(74)

Collection and Handling

The volume of solid waste has required increasingly organized collection, handling, and management systems. Collection and handling procedures are well established, especially in large cities. Some of the many approaches are provided in such documents as follows: Decision-makers Guide to Solid Waste Management(76), Decision-makers Workbook: Resource Recovery from Solid Waste(77), Mineral Resources and the Environment.(73) In brief, while many challenges exist on the management of solid wastes, substantial progress is occurring.

Projections of Current Trends and Recommendations

Projections estimate that net waste disposal will slightly increase over the next few decades (Table 29).(75) Resource recovery will improve, but expected gross discards will probably exceed the percentage improvement in recycling technology. It seems that solid waste will be in sufficient quantities to challenge the development of technology to utilize its energy.

TABLE 29. PROJECTIONS FOR SOLID WASTE GENERATION, RECOVERY, AND DISPOSAL IN THE UNITED STATES(75)

	Estimated		Projected		
	1971 *	1973 *	1980 *	1985 *	1990 *
Total: Gross Discards	121 (133)	131 (144)	159 (175)	182 (201)	204 (225)
Less: Resource Recovery	7 (8)	8 (9)	17 (19)	32 (35)	53 (58)
Equals: Net Waste Disposal available for landfill, energy use, other challenges	113 (125)	123 (135)	142 (156)	151 (166)	152 (167)

*Units are 10^6 metric tons/yr (10^6 tons/yr).

Ref: Resource Recovery Division, Office of Solid Waste Management Programs, U.S. EPA, revised December, 1974. Projections for 1980 to 1990 based in part on contract work by Midwest Research Institute. Baseline Forecasts of Resource Recovery, 1972 to 1990. Final Report Revised, March, 1975.

SECTION 6

CONVERSION PROCESSES

Section 5 has been directed at characterizing the different materials which constitute biomass feedstocks. This section will be directed at describing the various processes which might be used to convert these feedstocks into usable energy forms.

These processes have been categorized as primary thermochemical, primary biochemical, and secondary conversion systems. The primary thermochemical processes have been defined as those which utilize elevated temperature to directly convert biomass materials into energy forms or intermediate products. Combustion is considered in this class. Primary biochemical processes use microbiological species or their biochemical agents to convert feedstocks to fuel products or intermediates. Secondary processes are defined as those which convert intermediate products from primary processes into fuel products. Ethanol fermentation of glucose is a member of this class.

The processes and the important variations of the more significant processes will be described. Important process variables and their approximate levels will be presented, as well as schematic flow sheets when available. For more highly developed processes, equipment descriptions are provided.

Apart from this information, approximate calculations were prepared describing "scenarios". These "scenarios" represent first-order approximations of commercial plants and were made based on a brief analysis of the primary biomass feedstocks available within defined regions and an assessment of the most likely conversion system which might be used for these feedstocks. These calculations should be broadened and made more explicit in later work.

PREPROCESSING OF THE SELECTED BIOMASS FEEDSTOCKS

Preprocessing in this study refers to all steps involved in preparing the biomass feedstock into an acceptable form for energy recovery. These steps include harvesting and/or collecting, size reducing, sorting, blending, and hauling of the raw material from the point of origin to the energy conversion plant. Each biomass feedstock requires unique preprocessing steps. For example, agricultural and forest product wastes are shredded while in the field, after the primary product is recovered. Biomass products derived from aquaculture and silviculture practice might be shredded at the time of harvesting. Urban wastes, in an idealized example are first collected, then delivered to a transfer station, weighed, shredded, separated into organic and non-organic fractions before processing for further size reduction and separation. This section will be limited to size reduction practices, and separation and drying techniques, since harvesting and transportation of biomass were briefly covered in Section 5.

Advantages for Size Reduction

Many advantages are derived when biomass feedstock is preprocessed. Some of the most readily identifiable advantages obtained from shredded biomass are:

1. Increased density while reducing volume up to 70%(78)

2. A uniform mix blended from a heterogeneous feedstock

3. Controlled moisture, odor and dust

4. Eased mechanical assist

Principles Involved in Size Reduction Equipment

Size reduction requires mechanical energy. There are three types of mechanical forces associated with biomass material size reduction. These three forces are tension, compression and shear. Usually, all three are interrelated when biomass material is mechanically shredded. Tension forces on a body tend to pull it apart; compression forces are the opposite--squeezing and crushing the body. Shearing is the act of cutting and usually is accompanied with the other two forces. The relationship of these three basic forces is illustrated in Figure 3.(79) These forces are usually

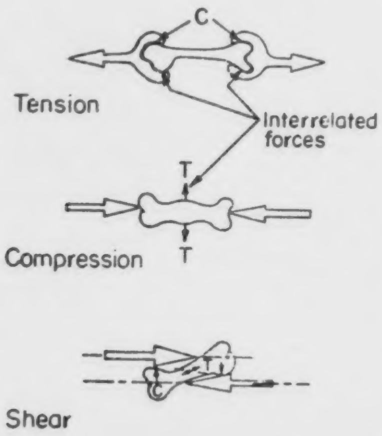


Figure 3. The application of forces in size-reduction operations.

combined in the various types of size reduction equipment. As an illustration of the variety of size reduction equipment currently available, the basic types and the potential for processing urban wastes are listed in Table 30.(79)

Primary Shredders

The most common and versatile piece of equipment used in industry for initial size reduction is the hammermill. It has been accepted by industry as the standard. For example, in the forest products industry, the hammermill is used for shredding wood bark and waste wood. Agricultural fibers, as wheat straw, hay, corn stalks are chopped in hammermill equipment.(80) Installations vary in capacity; the sugar cane industry has machines capable of processing 250 tons of waste cane per hour. However installations of 50 to 100 tons per hour are more common in the forest products industry.

Hammermills--

The hammermill is composed of five essential parts; a rotor with fly wheels, hammers attached to the rotor, a stationary anvil, the housing, and the grate bars. The chopping (or shredding) action of product occurs when the rotor turns at high speeds, striking the product and forcing it against the stationary anvil. The final product discharges through the openings in the grate bars. The housing, or main frame, supports the rotor and hammers and the stationary parts of the mill.

Numerous variations in the basic design are common; there are swing hammer and rigid hammer types; vertical and horizontal mills, each of which has certain advantages depending upon the feedstock source. Depending upon the position of the rotor, the hammermills are classified as either vertical or horizontal. Both types are being successfully operated, although more horizontal mills are available by manufacturers.(81) However, the function and the basic operating principles remain the same. The essential parts of the hammermill are shown in Figure 4.(79)

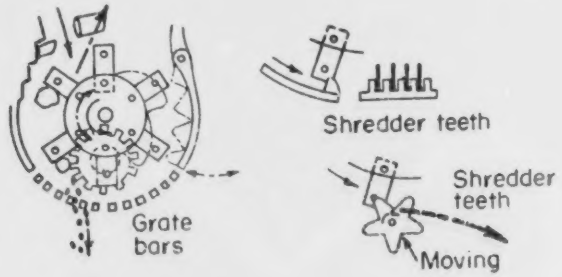


Figure 4. Hammermill principles.

TABLE 30. CURRENT SIZE REDUCTION EQUIPMENT AND POTENTIAL APPLICATIONS TO MUNICIPAL SOLID WASTE(79)

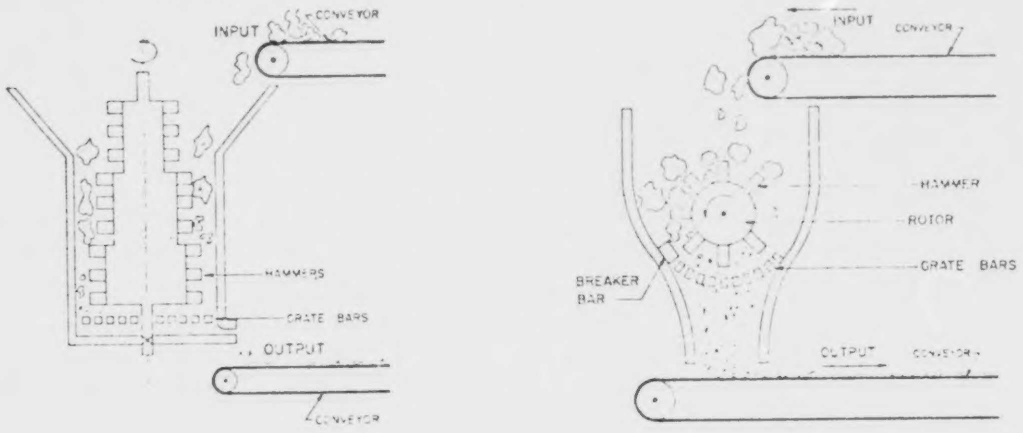
Basic Types	Variations	Potential Application to Municipal Solid Waste
Crushers	Impact	Direct application as a form of hammermill.
	Jaw, roll, and gyrating	As a primary or parallel operation on brittle or friable material.
Cage disintegrators	Multi-cage or single-cage	As a parallel operation on brittle or friable material.
Shears	Multi-blade or single blade	As a primary operation on wood or ductile materials.
Shredders, cutters, and chippers	Pierce-and-tear type	Direct as hammermill with meshing shredding members, or parallel operation on paper and boxboard.
	Cutting type	Parallel on yard waste, paper, boxboard, wood, or plastics.
Rasp mills and drum pulverizers		Direct on moistened municipal solid waste; also as bulky item sorter for parallel line operations.
Disk mills	Single or multiple disk	Parallel operation on certain municipal solid waste fractions for special recovery treatment.
Wet pulpers	Single or multiple disk	Second operation on pulpable material.
Hammermills		Direct application or in tandem with other types.

Vertical Shaft and Horizontal Shaft Hammermills--

There are two basic designs currently in use with urban refuse shredding, the vertical and the horizontal shaft. Both designs are successfully operated, and it is difficult to identify one as being better than the other. However, the horizontal shaft hammermill is more common than the vertical.(81) The two basic differences are diagrammed in Figure 5.

Franconeri(81) suggests a comprehensive check-list to aid in the selection of shredding equipment for processing biomass feedstocks. Advantages cited for the vertical shaft hammermill include:

1. A discharge conveyor is often not required.
2. Requirements for concrete foundations are reduced.
3. The total required building enclosure height is reduced because the machine discharges shredded material from the side instead of from the bottom as is the case with horizontal shaft shredders.
4. Electric power requirements are reduced due to design efficiency. While this advantage is not reflected in the shredder cost, it will be realized in the total system expense.
5. The shredder is much less subject to damage because difficult-to-shred items will pass through the machine and/or be rejected.
6. A more even distribution of wear and significantly lower hammer wear rates are possible because input material is gradually reduced in particle size as it passes from input to output, and one force is spread over the entire rotor area.



VERTICAL SHAFT HAMMERMILL

HORIZONTAL SHAFT HAMMERMILL

Figure 5. Vertical and horizontal shaft hammermills.

However, there are possible disadvantages associated with the vertical shaft mill and these should be mentioned. Replacement of the lower bearings is a major repair item, requiring considerable down time. Replacement and/or resurfacing of the lower hammers is difficult, since the space at the lower end is restricted due to the housing shape.

Other Types of Size Reduction Equipment

After the product is processed in the primary shredder, a secondary size reduction is often needed. Primary shredding reduces the product to approximately 6 inches. A second shredding operation will reduce the product to about 2 inches, with some smaller particles. The conversion process and the feedstock will dictate the need for further size reduction. Equipment for secondary reduction stages are available and are classified into five basic types. These types are hydraulic action pulpers, knife cutters, rasp, revolving drum pulverizer, and hammermills.

Knife Cutters, Choppers--

Knife cutters are particularly useful if only one type of waste feedstock is fed to them. The knife cutters are commonly found in the wood product industry. The familiar yard waste chippers is an example of the knife cutter. The knife cutter is best suited on feedstock which has a fibrous structure. The efficiency of the machines is dependent upon the sharpness of the knives blades, and knife maintenance tends to be an expensive factor. For field harvesting of aquatic plants, (either hyacinth or kelp), the shear-bar forage chopper appears applicable. It has been used successfully in hyacinth harvesting, and has been noted to cut cleanly and uniformly, producing particles of one inch length. This chopper, when modified, can chop 50 to 60 tons of water hyacinths per hour. The energy required by this one machine is 0.46 HPhr/ton.(82)

Rasps--

The rasp mill has the capability of accepting a variety of feedstock, including urban refuse. The rasp mills are huge cylindrical machines, some with diameters of 20 feet. This machine is common in European composting installation, with one installation of this design in the United States (Johnson City, Tennessee). The machine processes feedstock to smaller size (2 inches) by rotating massive cutting arms over rasping pins which forces product through discharge holes in a bottom plate. This machine is useful as a secondary size reducing machine. Units with 100 HP are capable of processing approximately 15 tons per hour.(79)

Wet-Pulpers--

The wet-pulper, a common piece of size reducing equipment originally developed for the paper making industry, is currently used for preprocessing urban refuse. The wet-pulper is part of the "Hydraposal System" of the EPA's Franklin, Ohio demonstration project. The purpose of this project is to recover resources from urban wastes using a wet processing system.(83)

Essentially, the wet-pulper is a large tube-like container (up to 12 feet diameter) with high speed cutting blades in the bottom. The wet-pulper can be visually compared to a huge kitchen garbage disposal unit.

The refuse, mixed with excess water, is shredded into a pumpable slurry. The solids content is low, averaging 2%. Fibrous feedstocks are best suited for this type of preprocessing equipment. If mixed refuse is a feedstock, then a pregrinding and a presorting operation is required. Figure 6 is a cutaway view of the Franklin hydropulper.(83)

A second variation of wet pulping is a combined system. In this separation system as applied to urban waste, the refuse is shredded to a particle size of 3 to 6 inches. From this stream, the tin cans are removed magnetically before being conveyed to the hydropulper. Excess recycle water is mixed with the refuse and pulping commences. The effluent from the hydropulper is fed to a liquid cyclone where the stream is split. The underflow, which contains the heavier solids as aluminum, glass and small ferrous metals, is sent to a recovery unit, while the overflow is sent to a series of screens and filters for the recovery of the organic constituents. The organics, mostly cellulose fibers, are then sent to a digester or to a paper processing plant, dependent upon the type of recovery desired. Figure 7 is a schematic diagram of the wet-separation process.

Disk Mill--

Disk mills are massive, stationary machines specifically designed for producing either fine grains or refined pulp. This machine is commonly found in the paper making and food processing industries. The feedstock to be processed by this machine is restricted to a material with uniform size, usually less than 2 inches. This restriction is due to the small sized opening port for product entry. The product to be processed is fed into the center of two high speed rotating disks, where the product is torn to small bits. Final product size is regulated by adjustment of the distance between the disc(84) (Figure 8). Disk mills, with power requirements of up to 4000 hp can be commonly found in large paper mills.(79)

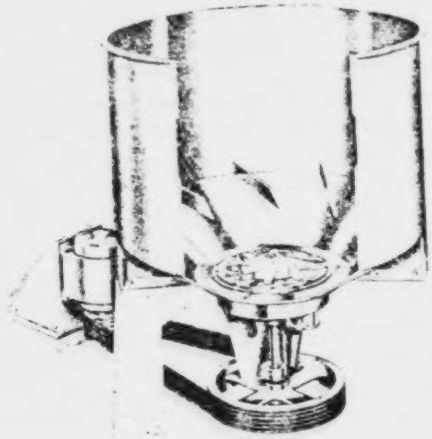


Figure 6. Cut-away view of wet-pulper.(83)

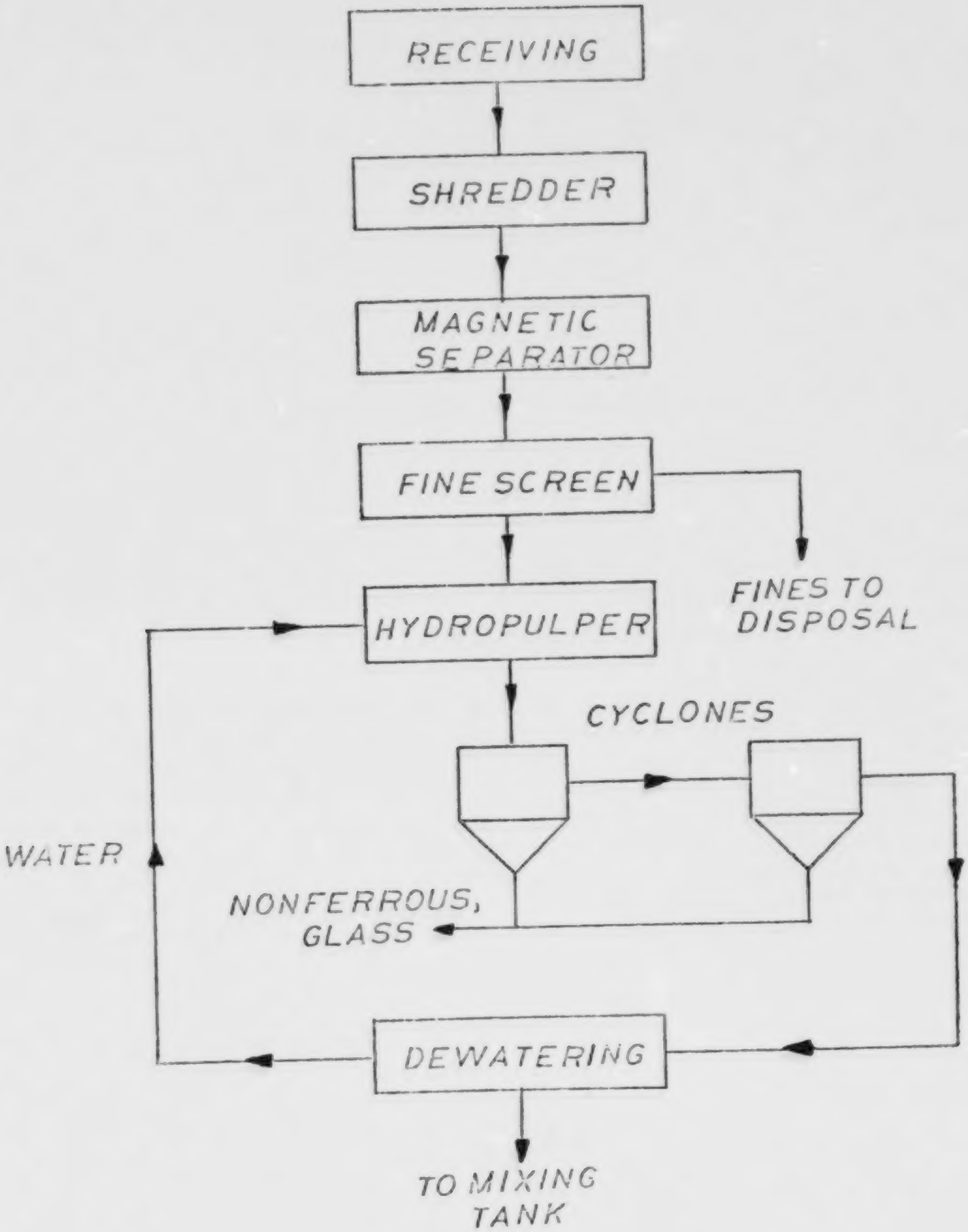

RECEIVING
SHREDDER
MAGNETIC SEPARATOR
FINE SCREEN
FINES TO DISPOSAL
HYDROPULPER
CYCLONES
WATER
NONFERROUS, GLASS
DEWATERING
TO MIXING TANK

Figure 7. Schematic diagram of wet separation system.

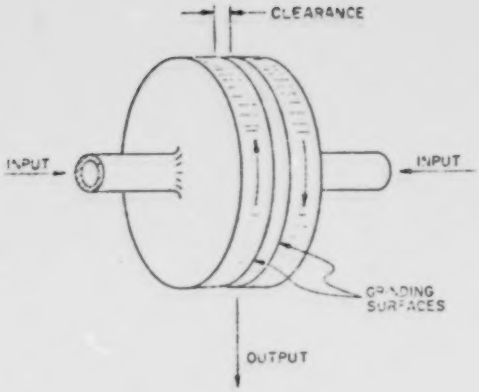

CLEARANCE
INPUT
INPUT
GRINDING SURFACES
OUTPUT

Figure 8. Disk mill schematic.

Pulpable feedstock, as derived from agricultural, silvicultural or forest product wastes could be processed in this type of machinery, since the primary shredding has been done in the field usually at the time of harvest.

Drum Pulverizers--

Drum pulverizers, or rotating drum mills are popular size reducing machines found in European waste processing plants. The drum pulverizer is similar in operation to that of the rasp mill and accept a variety of feedstock material. The operation is slow, and size reduction is accomplished by the tumbling action of the feedstock material inside of the rotating drum (10 feet diameter). Increased grinding action of the feedstock material is accomplished by the addition of internal baffles in the drum, and/or stationary central blades. Final size of the feedstock material is regulated by the diameter of the perforations in the rotating drum wall (Figure 9).(79)

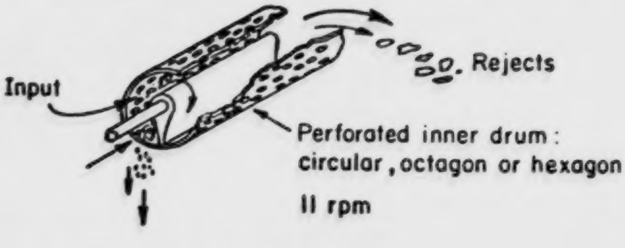

Rejects
Input
Perforated inner drum: circular, octagon or hexagon
11 rpm

Figure 9. Drum pulverizers.

Separation Techniques as Applied to Municipal Wastes

Essentially, there are three general classifications for separating the organic from the non-organic fractions found in municipal wastes. These are, (1) manually hand-sorting the refuse off a moving belt, (2) grinding the as-received refuse, followed by a magnetic separation and air classification, and (3) grinding the as-received refuse in a wet-pulper followed by separation with various screens, cyclones and magnets.

Hand Sorting--

Hand sorting of refuse is now obsolete and would not apply to any large scale separation plant. Some of the factors cited are unfavorable economics, incomplete separation and human indifference. The prices received for the recovered materials do not match the wages required to recover them. While separation would be limited to only the larger items; most of the organics are packed tightly with the inorganic matter. The two plants operating a hand sorting operation in Montreal and Houston have found that the plants cannot operate economically and have ceased operation.(85)

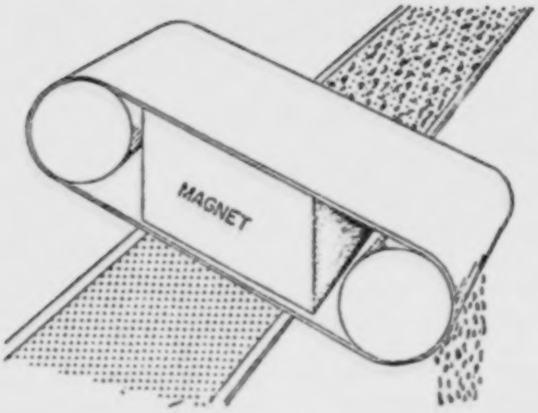
An automated plant, in which human judgments are replaced by electronic sensors coupled to a minicomputer, is operating experimentally at Massachusetts Institute of Technology.(85) In this plant, the large pieces of refuse are examined by the sensors, then categorized by a minicomputer. Subsequently, once the item is categorized, it is switched to an appropriate bin for baling.

A third type of sorting operation which is incorporated in some communities is that of segregating the refuse at the source, i.e., the home. In this method, the public as well as municipal workers, are educated to segregate their solid wastes into four categories - garbage, metal cans, bottles, and newspapers. With this system, separate collections are needed, thereby increasing collection cost. However, the ease of further processing is also increased.

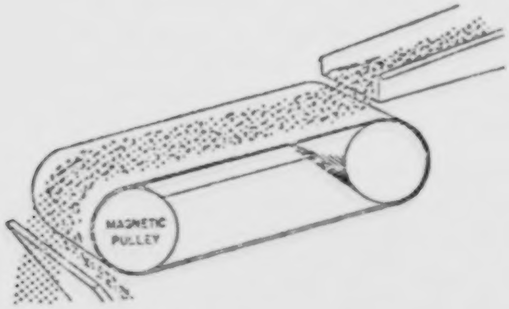
Magnetic Separation and Air Classification--

In the case of non-segregated compacted municipal trash which has been shredded at a central size reduction plant, separation of the metallics is achieved with the use of magnetic belts and air classification methods. The shredded trash which has been reduced to less than 6 inches particle size is conveyed through a magnetic field. The magnetic field may be either permanent or electro-magnetic. In this system, the tin cans are easily recovered. The use of magnetic belts for separation (Figure 10) is a well established method, as there are several companies specializing in the manufacture of this equipment.

After the magnetic items have been removed from the trash, the next step in the separation process is air classification. In this method, the trash is separated in different density gradients. The shredded trash is fed into an air current in which the trash is fluidized. The lighter fractions, such as paper and plastics, are carried out of the unit, while the heavier materials, such as rocks, glass and aluminum cans drop to the bottom.



SUSPENDED-TYPE PERMANENT MAGNETIC SEPARATOR


MAGNETIC PULLEY

PULLEY-TYPE PERMANENT MAGNETIC SEPARATOR

Figure 10. Two types of magnetic separators.

The National Center for Resource Recovery, Bureau of Mines, and the Columbus, Ohio's Solid Waste Transfer Stations all use separation systems based upon these techniques. Diagrams of the various types of air classifiers currently in use are shown in Figure 11.

Screens--

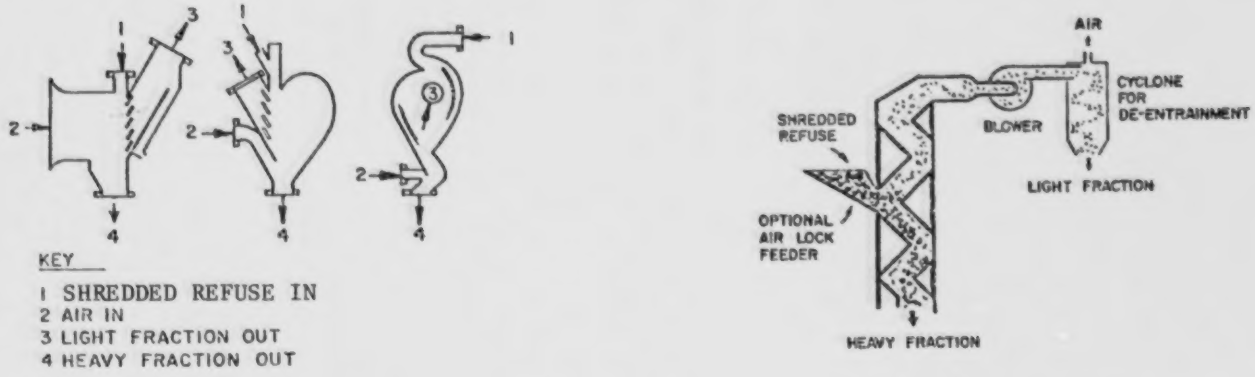
Air classified-shredded municipal trash contains dirt and other non-organics, which are usually concentrated in the minus 0.5 inch particle size range. This fraction, if not removed, contaminates the shredded trash when used in energy or fiber recovery processes. Furthermore, the dirt adds unnecessary ash. Thus the removal is often important. A method of removing this fraction can be accomplished by screening. Several screening techniques are available, such as flat-bed vibratory and the inclined, cylindrical, rotating screens. A study comparing the two techniques is described in a report by the University of California, Berkeley.(86) This study demonstrated a 96% removal of the minus 0.5 inch particle size range in a rotating cylindrical inclined rotating screen. As a comparison, a flat-bed vibratory screen removed 72% of the minus 0.5 inch particle size fraction from the same feedstock (air classified, municipal trash). No noticeable effects on screening efficiency were observed when the moisture content was varied between 20 to 30%.

Wet Separation Methods--

There are several processes based upon the use of water for separating the organic portions found in municipal trash. The Black-Clawson system in Franklin, Ohio is the first of its kind, and therefore it is referenced in the literature frequently. Another system which combines hand sorting and water floatation technique is the Tracy system.

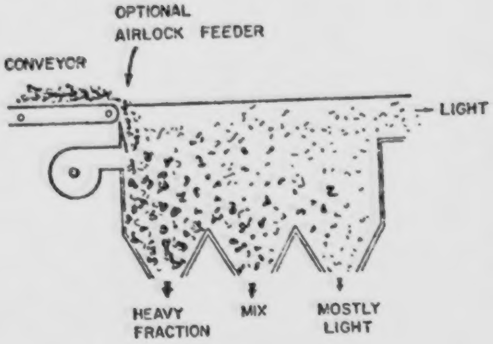
In the Black-Clawson method, segregated urban wastes (with large trash items as tires, stuffed chairs, refrigerators excluded) are shredded in a hydrapulper described in earlier paragraphs. Excess water is mixed with the urban wastes, and shredded to a slurry. This slurry is further refined to remove the inorganics, such as glass, dirt and metals through a series of wet cyclones, hydrascreens, and filter presses. The final recovered organic product is a cellulose fiber suitable for use in construction paper, such as asphalt roofing shingles. For an energy recovery process, the cellulose could be suitable for a biological digester, such as an anaerobic methane gas producer.

The Tracy separation system represents a different concept in wet separation systems. First, the refuse is hand sorted; large items like bundled newspaper, automobile tires, etc., are removed for salvage. The semi-selected trash is then pushed into the trough so that a float and sink separation is made. The float portion, which contain the organics, is skimmed and fed to choppers, then screened and finally pumped to an anaerobic digester for stabilization. The sink portion, which is mostly inorganics, is removed by dragline, and magnetically separated for the iron constituents. The non-magnetic material is then hand-picked before final disposal.(85)


1
2
3
4
KEY
1 SHREDDED REFUSE IN
2 AIR IN
3 LIGHT FRACTION OUT
4 HEAVY FRACTION OUT
AIR
CYCLONE FOR DE-ENTRAINMENT
SHREDDED REFUSE
BLOWER
LIGHT FRACTION
OPTIONAL AIR LOCK FEEDER
HEAVY FRACTION

VANE/ROTATIONAL AIR CLASSIFIER

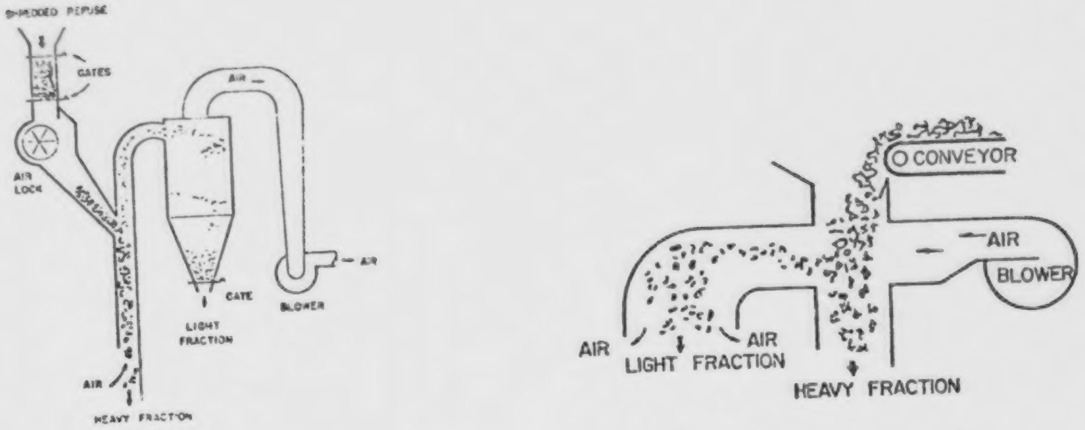
ZIG-ZAG AIR CLASSIFIER


OPTIONAL AIRLOCK FEEDER
CONVEYOR
LIGHT
HEAVY FRACTION
MIX
MOSTLY LIGHT

HORIZONTAL AIR CLASSIFIER[1]

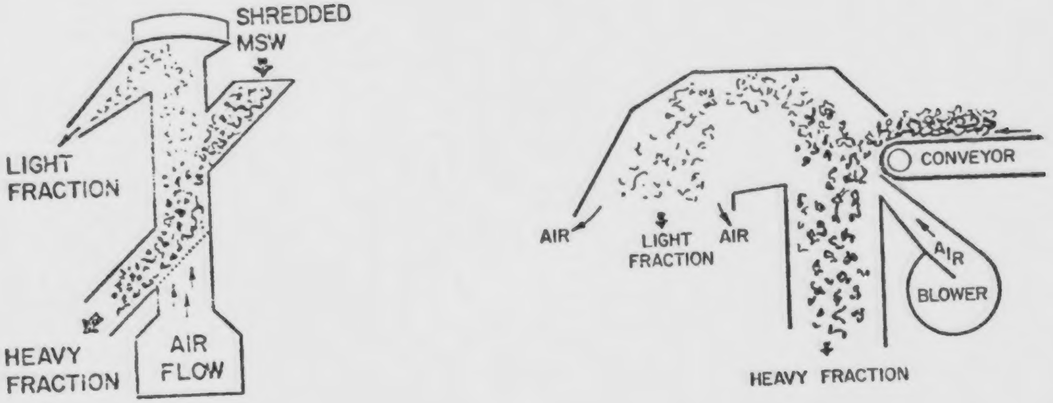
[1] From catalogs and information furnished by Eriez Magnetics Company, Erie, Pennsylvania 16512.

Figure 11. Various types of air classifiers.


SHREDDED REFUSE
GATES
AIR LOCK
AIR
GATE
BLOWER
AIR
LIGHT FRACTION
AIR
HEAVY FRACTION
CONVEYOR
AIR
BLOWER
AIR
LIGHT FRACTION
AIR
HEAVY FRACTION

VERTICAL AIR CLASSIFIER

CROSS FLOW AIR CLASSIFIER


SHREDDED MSW
LIGHT FRACTION
HEAVY FRACTION
AIR FLOW
CONVEYOR
AIR
LIGHT FRACTION
AIR
AIR
BLOWER
HEAVY FRACTION

SORTEX AIR CLASSIFIER

IMPULSE TYPE AIR CLASSIFIER

Figure 11. (continued)

Comparison of Wet and Dry Shredding Processes--

The question which arises when preprocessing methods for size reduction and separators are considered is which would be the preferred method - wet or dry shredding. The answer to the question will depend upon many factors. Two of the more important are the type of energy conversion/recovary process considered and the physical characteristics of the biomass feedstock available. Obviously, if the energy/recovery process is either thermochemical or the feedstock is a dry material, then a dry shredding process would be selected. Conversely, if the energy/recovery process is biological, as an anaerobic fermentation, and the feedstock source is a wet material, then a wet shredding process would probably be the method of choice.

Many studies have been concerned with processing of municipal wastes, either for resource or energy recovery. Both wet and dry processes which include shredding and separation have been considered. Black-Clawson Company is pursuing the wet-pulping and separation method, while the U.S. Bureau of Mines and the National Center for Resource Recovery are investigating the dry processing method. Both methods show a high degree of success.(87) A general comparison of the wet and dry preprocessing methods is presented in Table 31.

Drying of Biomass Feedstock for Thermo-Chemical Process

The net available energy value from a fuel, in this case the biomass feedstock, is affected by the moisture and ash content. Both moisture and ash dilute the available energy when the biomass is delivered to a thermochemical process. The ideal solid fuel is one with zero moisture and ash. Air classified municipal refuse averages 25 to 30% moisture and 25% ash. Vaporization of the moisture in a fuel consumes a portion of the available energy. A 30% increase in the available heating value is obtained when a fuel with a 30% moisture content is reduced to zero moisture content. The relationship of available energy and moisture content for a refuse derived fuel (RDF) is shown in Figure 12.

Removal of all of the moisture currently is impractical. This is due to two factors, the reduced drying rate at lower biomass moistures contents, and the hydroscopic nature of many biomass materials. For example, dry newsprint placed in a 50% relative humidity environment equilibrates at 8% moisture.

There are many manufacturers who specialize in the construction of drying equipment. Types of dryers which are available are categorized as - air, fluid bed, rotary, spray, conveyor, flash, drum and vacuum and are offered by more than 85 companies.

It should be noted in passing, that the heat required for drying also represents an energy demand. In thermochemical processes (e.g., those most likely to require drier feedstocks), the heat is generated in and transfers from process feedstock. Heat transfer rates are usually quite high. Conversely, drying in separate preprocessing equipment will usually require at least two, and possibly several, additional steps. For example, combustion of a portion of the feedstock, transfer of the heat to a gas stream, and then drying of the remaining feedstock. Generally, the overall thermal efficiency

TABLE 31. COMPARISON OF WET AND DRY SHREDDING METHODS IN RELATION TO PREPROCESSING OF WASTE BIOMASS FEEDSTOCK

	Wet Preprocessing	Dry Preprocessing
Feedstock Characteristics	Primary shredding required	Primary shredding required
	Fibrous material, as cellulose shred faster; Hydrogen bonds are loosened in water.	Feedstock can be variable
	Moisture content not critical	Low moisture feedstock shreds faster, but increases machine wear due to the abrasive nature of the feedstock
	Slurry, 2% solids content	Particle size adjustable, dependent upon moisture contents and grate openings
Final Product	Dewatering equipment is required to increase solids concentration	Final moisture can be adjusted to desired concentration
Process Energy (Heat of Friction)	Recovered in slurry, which can be useful if digestion conversion process is used.	Reduces moisture content of product

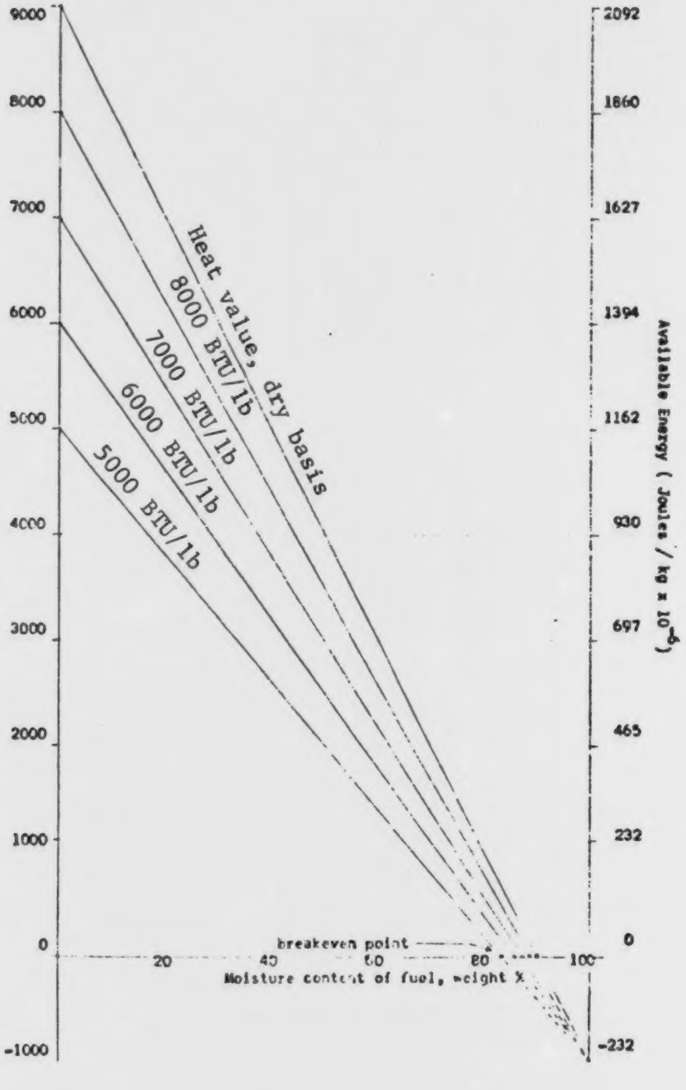


Figure 12. Available energy of refuse as a function of moisture content, considered as a binary system.

will be lower than in-process drying. Consequently, only when economics so dictate, or when a supplemental heat source is available, e.g., waste heat, or solar-aided techniques, will the drying add to the thermal efficiency of the system.

Pretreatment of Cellulose-Containing Products to Increase Enzymatic and Microbiological Conversion Processes

Perhaps the one most important step in the waste-to-energy conversion process which uses cellulose-containing products is that of pretreatment. The pretreatment step is the most energy-consuming step and also is often a significant single cost factor in the economic evaluation of enzymatic and microbiological method for energy recovery.

Cellulose is one of the most abundant natural occurring energy resources and, for our purposes, occurs in two forms, the pure form obtained from plant life and waste. The wastes occur as a residue from forest product and the agricultural industries, as a fraction of urban refuse, and in cattle manures.

Some of the synonyms used for cellulose after pretreatment are crude cellulose, complex carbohydrate, holocellulose, carbohydrate fraction in extracted wood, alpha cellulose, lignin-free cellulose, hemicellulose and simple or mixed polysaccharides. As a convention, alpha celluloses are referred to as those celluloses derived from woody plants, while the terms, crude or holocellulose, are derived from agricultural crops.

Each of these cellulose-containing products derived from any of these sources, requires unique pretreatment procedures specific for that product. Thus, there is no single uniform pretreatment method applicable to the general form of cellulose-containing products. A general discussion of various pretreatments available follows.

Pretreatment Methods--

The literature reveals a wide variety of chemical and physical means for modifying the complex chemical structure of the cellulose containing products. The purpose for modifying the chemical structure is to enhance the subsequent biological conversion to other useful products; untreated cellulose is resistant to biological attack. Chemical treatment causes the cellulose to swell, thereby weakening the chemical bonds, while physical treatment reduces the size and thus increases the surface area and the bulk density.

Chemical Treatment--

Alkaline chemicals, as sodium hydroxide and ammonia, have been successfully used for more than 50 years for cellulose utilization. Some of the first studies were designed to increase the nutritional value of straw for animal feed, and at one time sawdust, when conventional fodders were not available. In this method, straw is presoaked in a 1.5 percent solution of sodium hydroxide for at least 24 hours. The disadvantage of this method is that the solubilized hemicellulose is lost when the straw was washed for the purpose of removing excess sodium hydroxide. A variation of this original method was developed in which the straw was treated with a 20 percent sodium hydroxide solution, allowed to stand for a period of time, then neutralized with either silage or acetic acid. In another variation of this method, rice straw and sugar cane bagasse is treated with a 4 percent solution of sodium hydroxide and heated to 100 C. This pretreatment almost doubled the bacterial conversion of carbohydrate.(89)

Another variation of the alkali treatment method is the substitution of ammonia or ammonium hydroxide for sodium hydroxide. The advantage of substituting ammonia is that the nitrogen values are increased, and this adds nutrient value to the straw when used as either an animal feed or in a fermentation system. Another variation of the ammonia method is the application of heat and pressure of up to 70 psi.

Physical Pretreatment--

Physical treatment methods require the use of mechanical energy and the typical equipment available are hammer, ball and fluid energy mills. The purpose is to obtain micron-sized particles, sometimes less than 50 microns. The advantage of having small particles in an enzymatic or bacterial reactor is that the enzymatic activity is increased proportionately to the available surface active area. Milling history also effects the reactivity of the particle size - such items as the time and temperature profile while milling could change the crystallinity of the cellulose. These contributing factors are currently being investigated.

The major disadvantage of physically obtaining micron-sized particles is the high costs. Milling costs (1975) are listed by particle size in Table 32.(90)

TABLE 32. MILLING COSTS

Mesh Size	Inch	Micron	lb/hphr	Power Cost $/ton	Maintenance $/ton	Overhead Cost $/ton	Total Cost ¢/lbm
40	.0165	420	16	< $2.00	$1.40	$ .20	.18
80	.007	117	5	4.00	4.40	.40	.40
100	.0059	149	4	5.00	6.50	.50	.60
200	.0029	74	1	20.00	24.00	1.00	2.25
270	.0021	53	.55	36.45	45.00	1.40	4.14

Delignification--

An active area of research is the field of altering the lignin-cellulose bonds of woody plant cells. The lignin-cellulose bond is very resistant to enzymatic and bacterial attack. A few of the methods currently being investigated are (1) treating the wood residues with active chemical gases as chlorine dioxide or sulfur dioxide, and (2) direct fungal inoculation of wood residues in the holding area.

In the chlorine dioxide conversion method, the gas is passed directly into a bed of dried wood residue. The treated product was evaluated in enzymatic tests and marked improvements in digestibility were observed. However, later economic studies show that this method is expensive; one estimate was stated to be around $200/ton of product processed for chemicals alone.

In the sulfur dioxide treatment method, the gas is reacted with sawdust in a pressure vessel at 120 C and 30 psi for either 2 or 3 hours, dependent upon the sawdust being hardwood or softwood. After the reaction, the sawdust was neutralized with sodium hydroxide (although ammonium hydroxide would add nutrient value). The reacted sawdust was then evaluated in enzymatic digestion studies. The analytical results of the various wood species treated with sulfur dioxide are shown in Table 33.(89)

TABLE 33. COMPOSITION AND CELLULASE DIGESTION OF VARIOUS WOODS BEFORE AND AFTER SO_2 TREATMENT

Species	Lignin % Before	Lignin % After	Carbohydrate % Before	Carbohydrate % After	Digestibility % Before	Digestibility % After
Quaking aspen	20	7	70	71	9	63
Yellow birch	23	9	66	67	4	65
Sweetgum	20	5	66	64	2	67
Red oak	26	8	62	60	1	60
Douglas-fir	30	24	65	63	0	46
Ponderosa pine	31	19	59	58	0	50
Alfalfa	17	--	51	--	25	--

PRIMARY THERMOCHEMICAL CONVERSION PROCESSES

Direct Thermoconversion to Power

The most thermally efficient method of converting biomass to energy is by direct combustion for the generation of heat or steam. This method of solid waste treatment is the most expeditious means of minimizing the voluminous quantities of waste and refuse and is the most developed of the waste-to-energy processes. The most common application of biomass (municipal, industrial, agricultural, forest wastes, etc.) for direct energy production is as a direct boiler feed or a supplemental boiler feed for the production of steam either for on-site use or for the subsequent generation of electricity. Another application currently being explored is incineration of the waste to produce a combustion gas for directly powering a turbine-driven electric generator. Each of the direct-fired applications of waste biomass is examined in more detail in the following sections.

Direct Boiler Feed--

The use of biomass as a direct boiler feed for the generation of heat or steam has been widely practiced in the United States. Bagasse is commonly burned at sugar cane processing plants to provide process steam; tree bark and pulping liquors are combusted to supply steam for pulp and paper processing plants; wood chips, sawdust, and tree bark are used as primary fuel at plywood plants, particleboard plants, furniture plants, and sawmills; industrial and mining wastes are finding increased application as a raw feed for the generation of process steam and steam-generated electrical energy. More recently, some manufacturing facilities, not directly related to the use or processing of wood or other organic fuels, e.g., textile mills, are constructing wood-burning steam boilers.(91) Although other types of agricultural wastes have also been utilized on an experimental or limited basis for direct or supplementary fuel for boilers, e.g., peanut shells and livestock manure, most of the direct-fired applications of biomass waste in the United States utilize wood(92) or bagasse, with some use of municipal/industrial solid waste. Since the technology employed to recover energy from the less conventional waste feeds would be similar to that used for wood, bagasse or municipal/industrial solid waste, only the technologies applicable for handling the latter three wastes will be addressed in detail.

Bagasse--Bagasse is the refuse generated from the milling of sugar cane. It is comprised primarily of matted cellulose fibers and fine particles. A typical analysis of bagasse is shown in Table 34. Bagasse generally contains about 50 percent moisture and has a net heat content of about 2200 kcal/kg (4000 Btu/lb).

Bagasse is commonly burned at the sugar cane processing facility to augment the energy requirements for process steam production. The early incinerators were Dutch ovens. These were followed by the Cook furnace, a variation of the Dutch oven utilizing a refractory horseshoe-shaped hearth with air-admitting tuyeres located around the curved side wall.(93) This design, however, was plagued by high maintenance costs and was replaced by the Ward furnace.(94) The Ward furnace consists of individual refractory cells into which the bagasse is fed with approximately 85 percent of stoichiometric air. Initial combustion takes place in the cells and the remaining

TABLE 34. CHEMICAL COMPOSITION OF HARVESTED AND FIELD-DRIED BAGASSE (92)

Composition	Bagasse as Harvested	Bagasse Field-Dried
Proximate (%)		
Moisture	**52.0**	**15.0**
Volatile	**40.2**	**71.2**
Fixed carbon	**6.1**	**10.8**
Ash	**1.7**	**3.0**
Ultimate (%)		
Moisture	**52.0**	**15.0**
Hydrogen	**2.8**	**5.0**
Carbon	**23.4**	**41.4**
Nitrogen/oxygen	**20.1**	**35.6**
Sulfur	**Trace**	**Trace**
Ash	**1.7**	**3.0**
Heating value		
kcal/kg	2200	3930-4590
(Btu/lb)	**(4,000)**	**(7,080-8,260)**
Bulk density, stacked(d)		
kg/m^3		**200.4**
(lbs/ft^3)		**(12.5)**

combustion occurs in a secondary chamber or furnace located above the cells. A dumping hearth permits the ashes to be removed while the unit is in operation. Thermal efficiencies for natural draft operation are on the order of 57 percent,and, with the addition of an air heater and induced draft fan, may reach as high as 65 percent.

In recent years spreader stoker furnaces have been utilized to burn the bagasse; see Figure 13. These furnaces have reduced the overall excess air requirement from 50 to 100 percent down to 15 percent and have increased efficiency by 15 to 20 percent.(93) The stoker furnace, however, will not perform well with a moisture content in the bagasse feed in excess of 50 percent.

Wood Refuse--The largest single use for wood is for fuel; today about 43 percent of the world's wood is consumed as fuel.(95) In the United States, for the direct firing of boilers, wood ranks next to the three major fossil fuels, coal, oil, and natural gas.

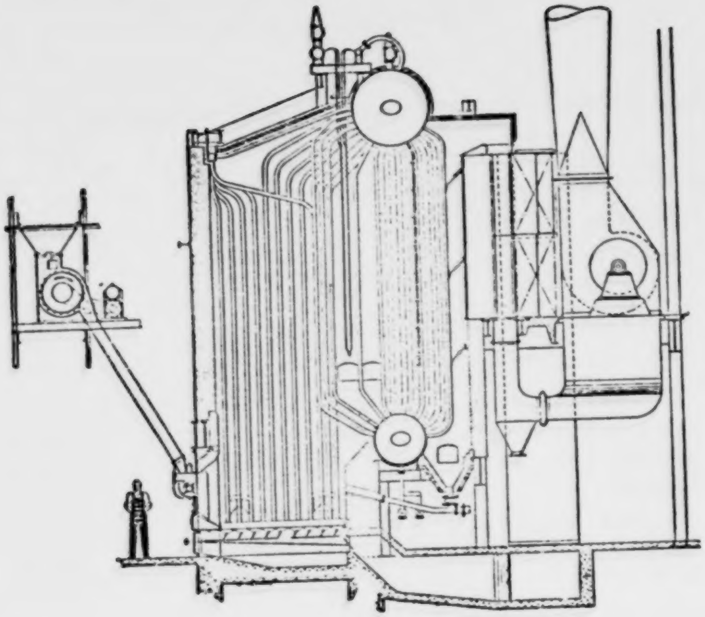


FIGURE 13. A C-E STEAM GENERATING UNIT WITH SPREADER STOKER FOR BAGASSE FIRING(92)

Typical compositions of various types of wood and bark and the resulting ash composition when burned are shown in Table 35. The moisture content has the most significant effect on the heating value of the wood and may vary considerably. Otherwise, the wood has a reasonably uniform composition and has heating values ranging from 4640 kcal/kg (8350 Btu/lb) to 5120 kcal/kg (9220 Btu/lb).

To maintain combustion, the moisture content of the wood generally must be kept below 60 percent. As the moisture content increases to 70 to 80 percent, the wood no longer has sufficient heat content to support its own combustion and becomes useless waste.(96) The wood can be dried, however, to a combustible state by a variety of means: (1) presses can be used to squeeze the excess moisture out of the wood and can potentially reduce the moisture down to 55 to 66 percent(97); (2) air drying can effectively reduce moisture content of freshly cut wood from 50 percent down to 25 percent in about a year(96); and (3) hot air, using heat from boiler flue gas, can be used to partially dry the wood.

Heat losses in the burning of wood consist mainly of those due to moisture in the stack gas and the sensible heat of the stack gas after

TABLE 35. CHEMICAL ANALYSES OF WOOD AND BARK OF VARIOUS TREE SPECIES TYPES[92]

Analyses (dry basis), % by wt	Wood and Bark						
	"Southern Pine" Bark	Pine Bark	Oak Bark	Spruce Bark	Redwood Bark	Redwood	Pine
Proximate							
Volatile matter	66.0	72.9	76.0	69.6	72.6	82.5	79.4
Fixed carbon	33.4	24.2	18.7	26.6	27.0	17.3	20.1
Ash	0.6	2.9	5.3	3.8	0.4	0.2	0.5
Ultimate							
Hydrogen	5.5	5.6	5.4	5.7	5.1	5.9	6.3
Carbon	56.5	53.4	49.7	51.8	51.9	53.5	51.8
Sulfur	0.0	0.1	0.1	0.1	0.1	0	0
Nitrogen	0.4	0.1	0.2	0.2	0.1	0.1	0.1
Oxygen	37.0	37.9	39.3	38.4	42.4	40.3	41.3
Ash	0.6	2.9	5.3	3.8	0.4	0.2	0.5
Heating value, kcal/kg (Btu/lb)	4943 (8900)	5016 (9030)	4649 (8370)	4855 (8740)	4638 (8350)	5121 (9220)	5071 (9130)
Ash Analyses, % by wt							
SiO_2	19.0	39.0	11.1	32.0	14.3		
Fe_2O_3	1.0	3.0	3.3	6.4	3.5		
TiO_2	*	0.2	0.1	0.8	0.3		
Al_2O_3	21.0	14.0	0.1	11.0	4.0		
Mn_3O_4	*	Trace	Trace	1.5	0.1		
CaO	27.0	25.5	64.5	25.3	6.0		
MgO	5.0	6.5	1.2	4.1	6.6		
Na_2O	3.0	1.3	8.9	8.0	18.0		
K_2O	9.0	6.0	0.2	2.4	10.6		
SO_3	6.0	0.3	2.0	2.1	7.4		
Cl		Trace	Trace	Trace	18.4		
P_2O_5	4.0	*	*	*	*		

combustion. Other losses consist of radiation and miscellaneous heat losses from the boiler and carbon loss in the ash. The various heat losses in a wood-burning boiler are identified in Table 36. The loss in boiler efficiency as a function of the moisture content of the wood is illustrated in Figure 14. This loss is largely attributable to the latent heat of vaporization of the water vapor in the stack gas. The loss of energy as a result of the sensible heat of the stack gases is determined by the volume and temperature of the stack gas. A high percentage of excess air and high stack gas temperature will result in a reduced overall efficiency. Some of the sensible heat may be captured by the use of heat recovery equipment such as combustion air preheater and economizers or feed water heaters, and modifications in the type of furnace can reduce the excess air requirements.

Wood waste is commonly burned in three types of equipment, pile, thin-bed, and suspension furnaces. Prior to 1940, the Dutch oven was the most common type of boiler used; see Figure 15. The wood is fed into the top of the oven where it collects on a pile on the water-cooled grate. Combustion air is fed through the sides of the cell and grate causing the wood to be gasified and combusted. The hot gases are fed into a secondary boiler section where they are combusted further. The Dutch oven partially gasifies or

TABLE 36. OVERALL BOILER EFFICIENCY AS A FUNCTION OF WOOD MOISTURE CONTENT (92)

Heat Loss Factors	Percent Lost		
	5% Moisture	25% Moisture	50% Moisture
Heat loss to dry stack gases[(a)]	9	9	9
Heat loss to moisture in fuel[(b)]	0.5	4	13
Heat loss from formation of moisture from hydrogen in the fuel[(c)]	7-8	7-8	7-8
Heat loss from incomplete combustion[(d)]	4	4	4
Heat loss from radiation and unaccounted for			
	21.5	23	34
Corresponding boiler Efficiency	78.5	75	66

(a) Based on 40% excess air, 400 - 500 F stack gas temperature.
(b) Based on stack gas temperature of 400 - 500 F.
(c) Based on Douglas fir bark fuel.
(d) Assumed.

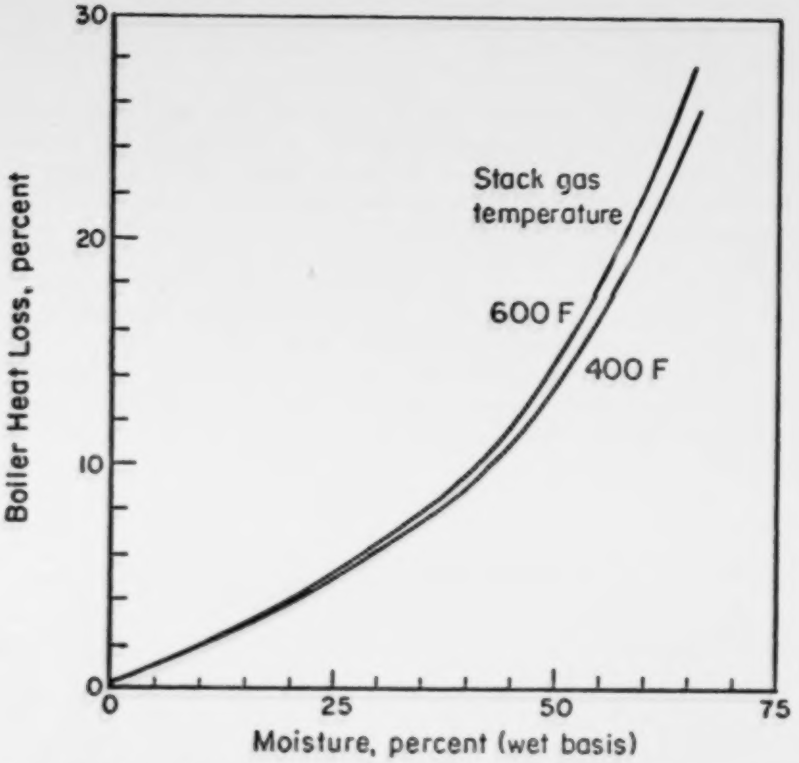


Figure 14. Boiler heat loss versus wood moisture content.(95)

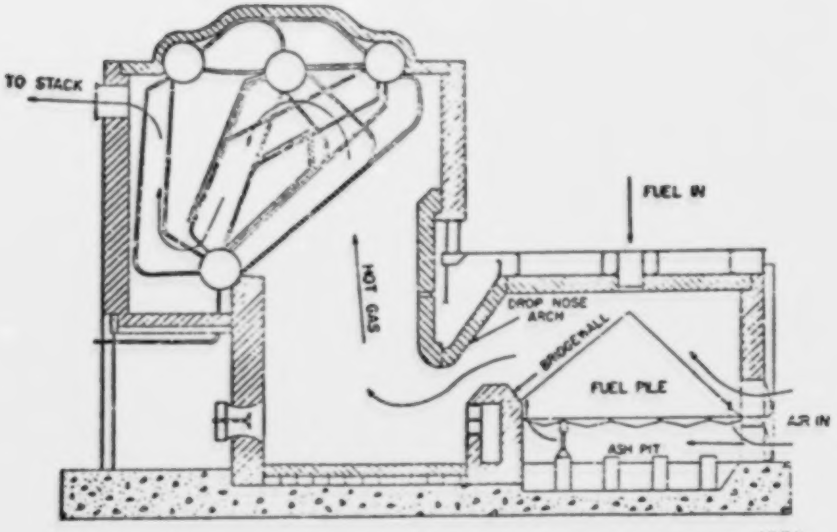

TO STACK
FUEL IN
HOT GAS
DROP NOSE ARCH
BRIDGEWALL
FUEL PILE
AIR IN
ASH PIT

Figure 15. Boiler with a Dutch-oven furnace.(95)

distills the wood and, therefore, can tolerate higher moisture contents than direct combustion. This method is not extensively employed in wood-fired boiler units today.

Most modern applications of wood firing utilize the thin bed type of furnace with a stoker. The most common of these is the spreader stoker shown in Figure 16. This fact is illustrated in Table 37, a summary of the percentages of boiler sales for various boiler configurations in five different size categories from 1965 through 1975. In stoker-fired arrangement hog fuel or wood chips are introduced well above the grate permitting the smaller particles to dry out and burn in suspension while the remainder of the fuel continues in flight to the grate where the combustion is completed. Various types of grates are utilized in stoker furnaces. In smaller size boilers (less than 100,000 lb of steam per hour), stationary or intermittent dumping grates are common. For larger boilers, traveling grates or self-cleaning grates are generally used. A boiler equipped with a traveling grate is shown in Figure 16.

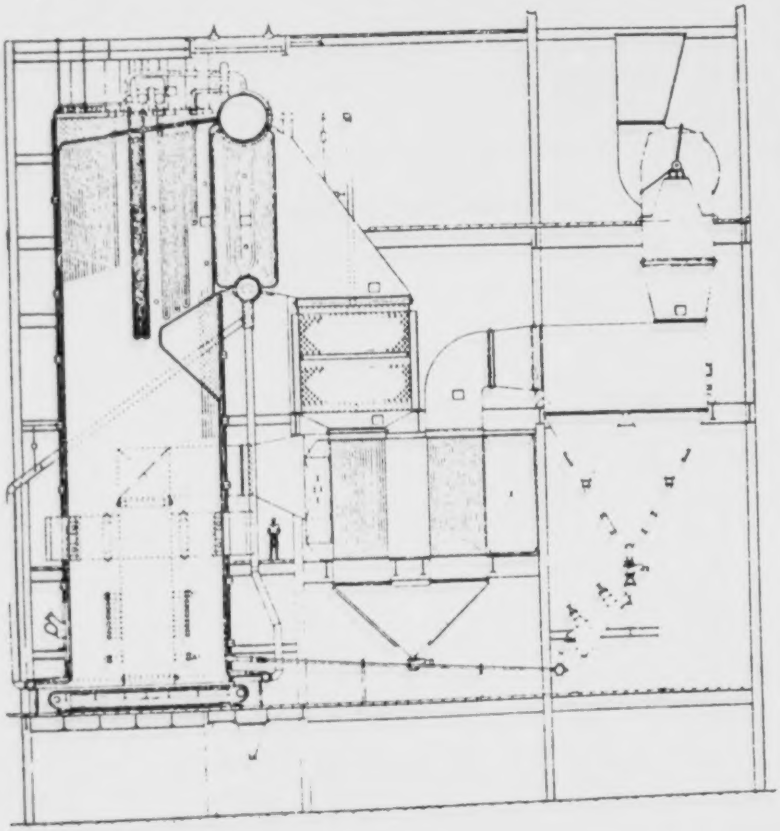


Figure 16. Wood-fired spreader stoker.(95)

TABLE 37. WOOD FIRING METHODS FOR DIFFERENT SIZE CATEGORIES FOR BOILERS SOLD BETWEEN 1965 AND 1975(92)

Firing Methods	Capacity x 10^{-3} lbs steam/hr 10-16	16-100	100-250	250-500	Over 500
Spreader Stoker	50.0	34.6	72.5	100.0	66.7%
Underfeed Stoker	0	1.9	0	0	0
Overfeed Stoker	0	34.0	20.0	0	0
Suspension	0	0	2.5	0	11.1%
Other	50.0	29.5	5.0	0	22.2 %

Heat release rates on spreader stoker type operations commonly approach 1,000,000 Btu per hour per square foot of grate area with 35 to 70 excess air and 400 F air temperature.(98) Generally, about 80 percent of the combustion air is supplied through the grate and 10 to 20 percent is injected over the grate to stimulate turbulence and mixing in the combustion gases inducing rapid combustion and reduction of smoke emissions.(95) Spreader stoker type boilers can handle wood up to about 55 percent moisture.(99) Moisture contents above 45 percent, however, decrease the combustion rate rapidly.(100) Under these conditions furnace temperature must be maintained above 750 to 1000 F to maintain stable combustion conditions.(98)

The thin fuel bed and rapid burning rates of the spreader stoker result in its being very sensitive to changes in boiler load. Control over boiler feed rates and air supply is necessary to maintain stable combustion conditions. A variation in the thin bed type furnace, the inclined type grate shown in Figure 17, however, characteristically has a deeper fuel bed than a spreader stoker. This large fuel inventory on the grate itself results in its being much less sensitive to load changes.

In all types of stoker applications, care must be taken to prevent overheating of the grate in localized areas. Often, the fuel becomes unevenly distributed across the surface of the grate resulting in irregularities in air flow. Overheating occurs in those areas where the air flow is restricted and may cause grate damage. Many times grates are water-cooled to alleviate this problem. Careful control of fuel size is also an important factor in preventing grate overheating by lessening the wide variation in fuel density on the grate. Minimizing the amount of slack or material under 1/4-inch

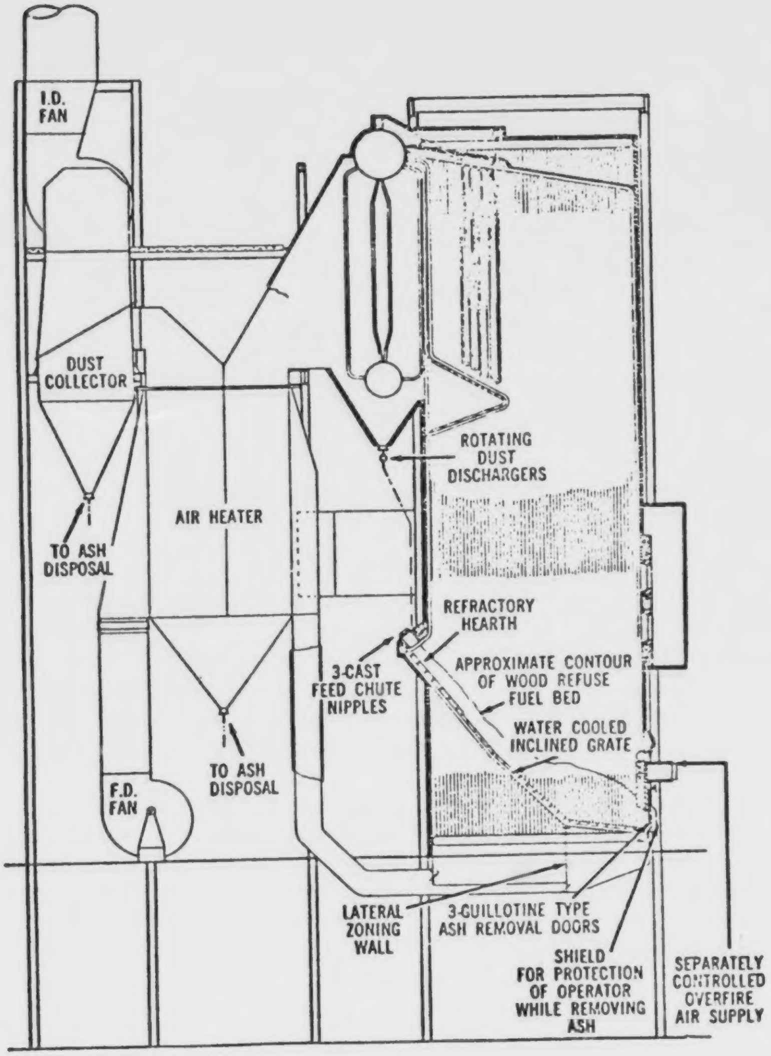

I.D. FAN
DUST COLLECTOR
TO ASH DISPOSAL
AIR HEATER
TO ASH DISPOSAL
F.D. FAN
ROTATING DUST DISCHARGERS
REFRACTORY HEARTH
3-CAST FEED CHUTE NIPPLES
APPROXIMATE CONTOUR OF WOOD REFUSE FUEL BED
WATER COOLED INCLINED GRATE
LATERAL ZONING WALL
3-GUILLOTINE TYPE ASH REMOVAL DOORS
SHIELD FOR PROTECTION OF OPERATOR WHILE REMOVING ASH
SEPARATELY CONTROLLED OVERFIRE AIR SUPPLY

Figure 17. Wood-fired inclined grate.(95)

diameter that enters in the fuel is most important. Usually, fuel sizes of less than about 1-1/4 to 2 inches with a maximum of 40 percent slack are specified for stoker applications.(101)

Suspension firing of wood is similar to pulverized coal firing. For successful suspension firing, the wood should be dried and reduced to as small a size as possible with a minimum of 50 percent of the wood particles smaller than a 1/4 inch.(101) Suspension firing results in a simpler, less expensive boiler than stoker firing, but requires more extensive hogging. It is recommended that an auxiliary fossil fuel, such as oil, natural gas, or pulverized coal, be fired in suspension along with the wood.(101) Normally, wood firing in suspension burning units should not exceed 40 to 50 percent of the total heat input to the boiler, the rest being carried by the auxiliary fossil fuel. A typical suspension fired wood boiler normally has a small dumping type grate installed at the base of the unit to handle excess wood ash or chips which may fall to the bottom without burning.

Urban and municipal solid waste--The solid waste disposal problem and the energy shortage have focussed attention on the utilization of solid urban and municipal waste as a direct boiler feed. Direct incineration is capable of reducing the volume and weight of refuse by as much as 92 percent and 80 percent, respectively, and the heat generated can be used to produce steam for heating and cooling or for generating electricity. The residue formed by the thermal reduction process is inert and may be landfilled or in some cases utilized as a construction material.

The recovery of waste heat in conjunction with the incineration of municipal refuse was initially tried on water-wall boilers in Europe, particularly in Germany, on combined municipal incinerator steam power generating stations. This was followed in the United States by both direct and combined refuse fired boilers. The first direct-fired water-wall solid waste incinerator was installed at the U.S. Naval Station in Norfolk, Virginia, in 1966.(102) This was followed by other larger installations in Chicago, Harrisburg, Nashville, Saugus, and several other cities.

The quantity of heat or energy that a biomass waste feed will produce when burned is a function of its moisture content, ash content, and degree of heterogeniety. A lower moisture and ash content in the waste will result in a higher heating value. A highly heterogeneous waste, containing a significant percentage of ash and inorganic noncombustibles, will have a lower heating value than a waste with a high organic content. The limits of these physical parameters as related to self-sustained combustion of refuse is illustrated in Figure 18, a three-coordinate chart showing the range of refuse that can be burned without auxiliary fuel.(103) The typically higher moisture contents and percentage of noncombustibles in the municipal solid waste limit their average heating value to about 4000 to 6000 Btu/lb,(104) and the heterogenieties and ash content result in a furnace and boiler efficiency of 65 percent as opposed to efficiencies in excess of 80 percent obtained with coal, oil, or gas.(103)

Two general combustor designs are used to recover energy from refuse. The first design employs a conventional refractory furnace followed by a

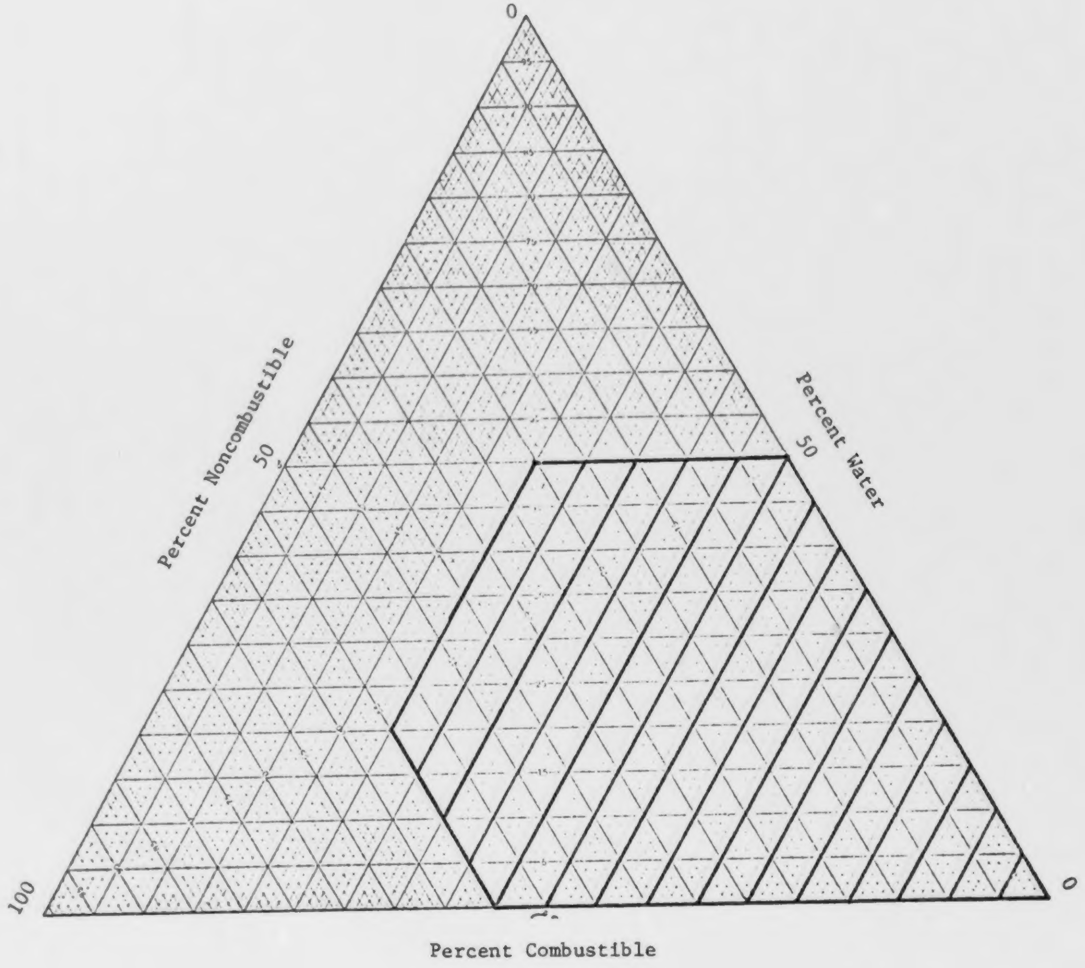


Figure 18. Composition limits for self-burning of refuse.(103)

waste heat boiler. The second and more recent design utilizes a water-wall furnace; see Figure 19. The wall consists of closely spaced vertical water tubes, each connected to the neighboring tube by welded steel fins. A moving grate at the base of the furnace evenly distributes, mixes, and conveys the burning refuse through the combustion chamber. The furnace is generally followed by a main heat exchanger, superheater, and an economizer. The water-wall furnace offers improved heat transfer efficiency over the refractory furnace and permits operation at lower percentages of excess air (150 as opposed to 300 percent).(102) These features result in more effective utilization of the waste feed and the generation of smaller volumes of combustion gases and subsequently smaller gas handling equipment. The disadvantages of the water-wall furnace is the slightly higher associated capital and operating costs.

Typical waste incineration furnaces are capable of accommodating a wide variety of heterogeneous waste feeds, e.g., commercial, residential, and industrial and two of the major problems with the combustion of solid municipal waste, the nonuniformities in composition and size and air pollution, have been largely obviated by the utilization of agitated stokers and stack gas cleanup equipment.

The boiler designs for various water-wall incinerator systems are fundamentally similar to each other and detailed information on one direct-fired installation, the Chicago Northwest incinerator, is provided below. Information on some of the other installations is presented in Table 38.(103)

The largest waste-to-heat installation in the United States is the Chicago Northwest Incinerator. The system was developed by the Ovitron Corporation and has been in operation since March, 1971. The 1450 metric tons per day (1600 TPD) plant consists of four 363 metric tons per day (400 TPD) incinerators producing a total of 440,000 lb/hr of steam and 77 metric tons per day (85 TPD) of metals.(103,105)

Shredded municipal solid waste, separated from the ferrous metals, is fed directly to the incinerator feed hopper (see Figure 20). From the feed hopper, the waste is introduced to the stoker by a hydraulic ram feeder. The reverse-reciprocating stoker is specifically designed for burning municipal refuse. The stoker is inclined and equipped with reverse-acting grate bars that push the refuse back up the inclined slope, creating a mixing and tumbling action. This action, coupled with the flow of air through the grate bars, ensures effective burnout of the waste.

The ash and residue are pushed off the grate into a quench tank from where it is hydraulically pushed up an incline slope and allowed to drain. This quenching and drying arrangement produces a residue with less than 15 percent moisture and also provides a water seal preventing the infiltration of air into the furnace.

To help dry and ignite the raw feed, the hot combustion gases are directed over the incoming refuse. The gases are then passed through the boiler section and economizer and introduced to an electrostatic precipitator for removal of particulates prior to discharge to the stack.

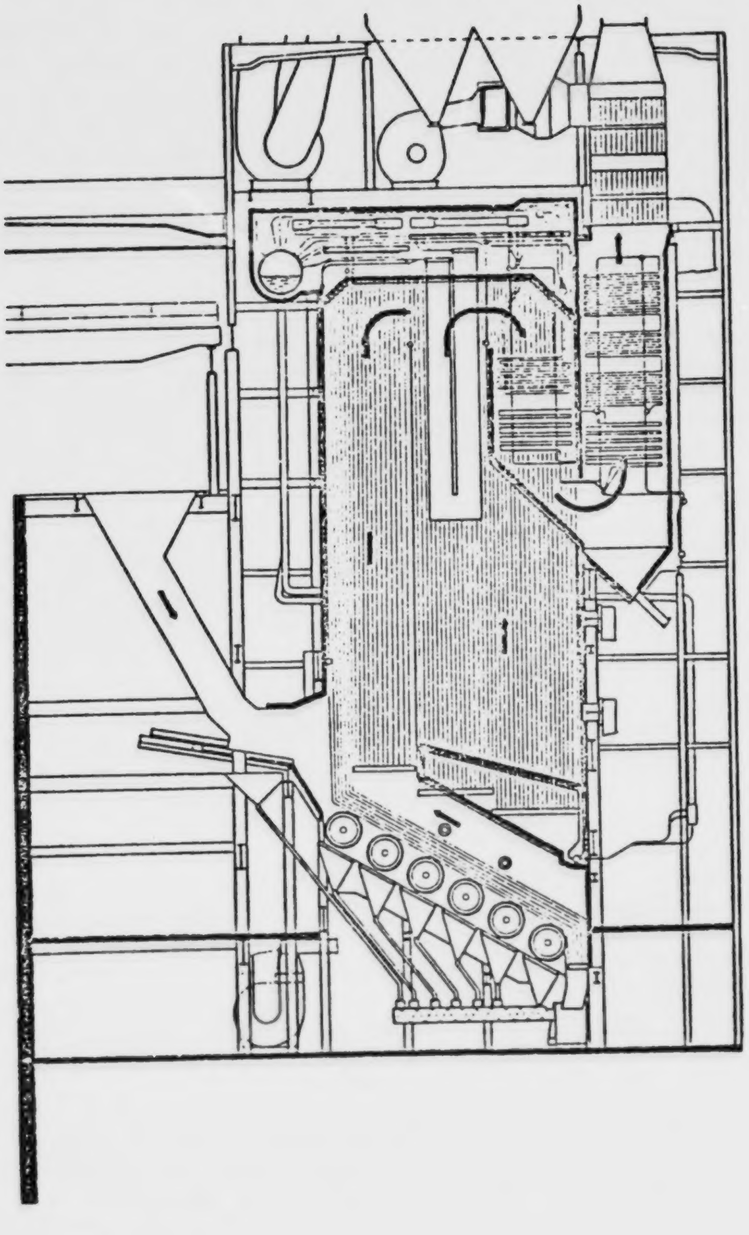


Figure 19. One form of water-walled incineration.(92)

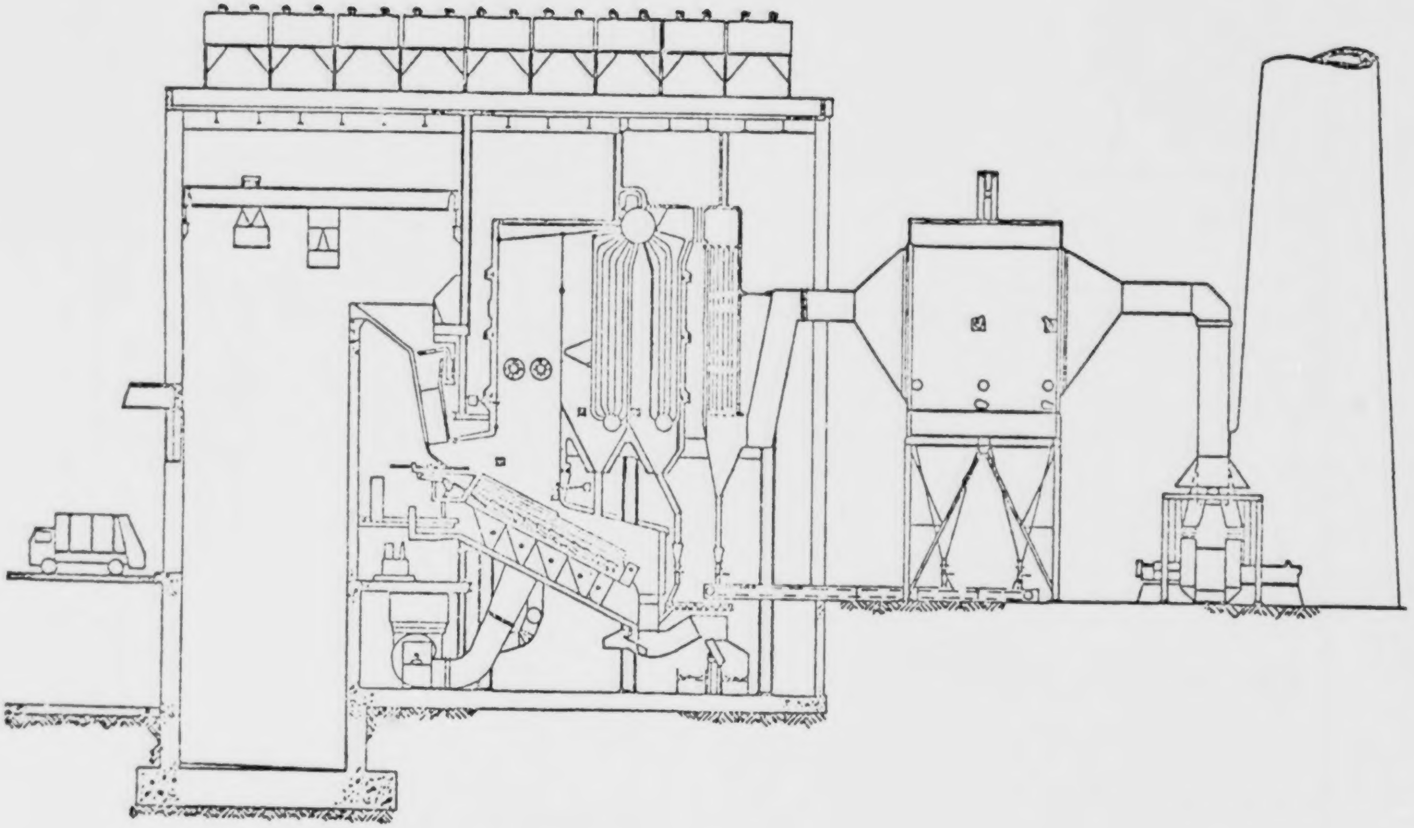


Figure 20. Chicago northwest incinerator.[103]

TABLE 38. SUMMARY OF SELECTED DIRECT-FIRED REFUSE TO ENERGY COMBUSTION PROCESSES(103)

LOCATION	DATE OF START UP	STOKER	CAPACITY METRIC TPD TPD	PARTICLE SEPARATION TECHNIQUE	STEAM OUTPUT			USAGE	COMMENTS
					FLOW RATE kg/hr x 10^{-3} lb/hr x 10^{-3}	TEMP °C °F	PRESSURE kg/m² x 10^{-6} Psig		
Montreal Canada	1971	Von Roll	4x272 4x300	Electro-Static Precipitator	45 100	260 500	1.55 225	Heating & Auxiliary Power	10-15% of input - ash & scrap metal
Chicago Northwest Incinerator	1972	Martin	4x363 4x400	Electro-Static Precipitator	200 440	204 400	1.7 250	Limited	Recovered Magnetic Metals
Harrisburg Penn.	1972	Martin	2x326 2x360	Electro-Static Precipitator	63 138	232 460	1.7 250	Auxiliary Power	
Nashville Tennessee	Late 1974	Von Roll	2x326 2x360	Wet Scrubbers Dry Cyclone	99 218	185 SAT 365 SAT	1.03 150	Auxiliary Collant, Steam	$16.5 Million
Saugus Mass.	1975	Von Roll	4x272 4x300	Electro-Static Precipitator	102 225	427 800	4.3	Power	

The boiler, approximately 12 meters (40 feet) in height, is constructed of membrane water-walled tubes with extruded fins. The refractory surface is limited to 4.6 meters (15 feet) above the grate to prevent corrosion of the water walls when burning plastics. The boiler is designed with five passes, providing for a maximum amount of heat recovery. Each pass is provided with a hopper to collect fly ash which is automatically returned to the ash discharger where it is mixed with the other plant residue and trucked to a landfill site.

There is no present market for the steam, and that not utilized in plant to drive turbines for pump and blower operation is condensed in air-cooled exchangers.

Supplemental Boiler Feed--

The use of refuse as a supplemental boiler feed has been more widely practiced in Europe than in the United States. Large size installations in Munich and Stuttgart, Germany, and Zurich, Switzerland, have been on stream since the 1960's. The only major on-stream facility in the United States utilizing refuse as a supplemental fuel is in St. Louis, Missouri, at Union Electric's Meremac Plant.(103) Other projects, proposed or under development, are listed in Table 39 along with a summary of some of the larger on-stream installations.

TABLE 39. WORLDWIDE INSTALLATIONS OF REFUSE-FIRED BOILERS (105)

I. ENERGY RECOVERY PROCESSES

No.	Name	Principal Product(s)	Other Products	Capacity (Tons/Day)	Capital Costs ($/Ton/Day)	Operating Costs ($/Ton)	Revenue ($/Ton)	Net Costs ($/Ton)	Development Status
1	American Thermogen	Steam	Frit	1,650 (Proposed)	11,800	6.42	3.01	3.41	Pilot plant
2	Chicago N.W. Incinerator	Steam	Fe Metals	1,600	14,400	NA	NA	NA	Plant completed March 1971
3	Montreal Incinerator	Steam		1,200	12,500	7.00	3.50	3.50	Plant completed February 1970
4	Issy-les-Moulineaux	Steam Electricity		1,500	15,300	7.70	2.88	4.82	Plant completed 1965
5	Munich North Incinerator	Electricity	Metal	1,056	15,400	13.96	1.96	12.00	Plant completed 1967
6	Munich Power Station	Electricity Steam		960	NA	NA	NA	NA	Plant completed 1971
7	Zurich II Incinerator	Electricity	Steam	520	NA	NA	NA	NA	Plant completed 1969
8	Basel II Incinerator	Electricity	Steam	600	NA	NA	NA	NA	Plant completed 1969
9	Osaka Plant	Electricity		400	NA	NA	NA	NA	Plant completed 1966
10	Isogo Plant	Steam		450	NA	NA	NA	NA	Plant completed 1968

St. Louis supplemental fuel--The incoming municipal and industrial refuse is initially screened for the removal of large bulky items such as appliances, furniture, or tires and processed through a shredder or air classifier and a magnetic separator. The refuse, free of ferrous metals and shredded to a particle size of less than 2.5 cm (1 inch), is conveyed by pneumatic feeders into the two furnaces.

The 125 mw rated furnaces were originally fired with natural gas but were modified to burn refuse and coal. The refuse burning ports were installed in the corners of the furnaces, between the two middle coal burners. The milled refuse is burned in suspension, in the same flame pattern as the pulverized coal or gas, and as the furnace has no grates, the unburned particles fall to the bottom of the ash hopper (Figure 21).

At full load, the refuse is fed at a rate equivalent to 10 percent of the heating value of the coals or about 540 metric tons of refuse per day (600 TPD). Based on average heat value of 2700 kcal/kg (5000 Btu/lb) for the refuse, approximately one ton of coal is conserved for every two tons of refuse burned. The manufacturer of the boiler cited several reasons for the low percentage of refuse fired, among them being the corrosive potential of refuse, lack of homogeneity in refuse, moisture content of refuse, decreased fly ash resistivity, and the logistical and institutional constraints of reliably moving and processing large amounts of refuse.

In addition to the steam generated from the burning of the refuse, credit is also claimed for the ferrous metals recovered during the preprocessing step and the fly ash collected in the electrostatic precipitators. The coal bottom ash, previously used by the Missouri State Highway Department for snow-covered roads, is now unacceptable for application to the roads due to the presence of unburned wood, metal and other materials resulting from the burning of refuse.

The test operation on the two boilers was hampered by technical problems with feeding and conveying the refuse and did not operate at the full anticipated load of 540 metric tons per day (600 TPD) of refuse. The concept was, however, regarded by Union Electric management to be successful enough to warrant an expansion of the project to handle essentially all of the refuse generated in the St. Louis metropolitan region (2.2 to 2.7 million metric tons annually (2.5 to 3 million TPY)) and burn it in the Meremac and Labadie power plants.(106)

Little information was available on the environmental impact of burning the refuse coal combination except that SO_2 emissions are somewhat less and the particulate discharges are almost three times that experienced with pure coal.(107)

Direct Thermo Conversion to Electricity--

A process has been developed by the Combustion Power Company of Menlo Park, California, in which refuse is incinerated in a modular fluidized bed combustor and the hot gases passed through a gas turbine electric generating system. The process has been demonstrated on an EPA-sponsored 63.5 metric tons/day (70 tons/day) pilot plant using municipal waste as feed.

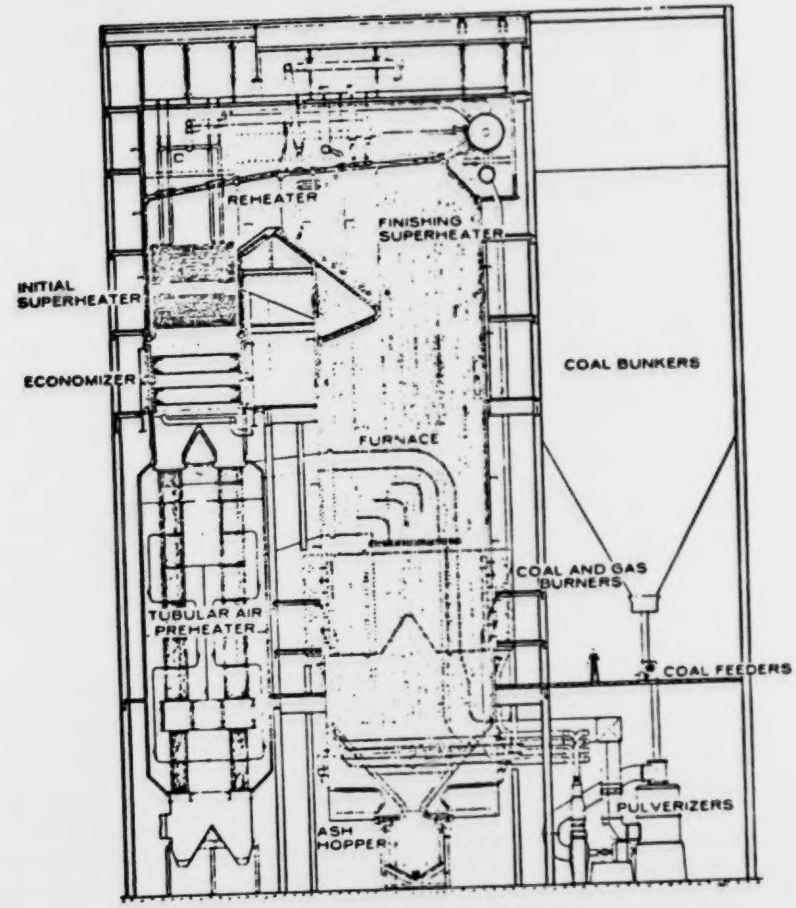

REHEATER
FINISHING SUPERHEATER
INITIAL SUPERHEATER
ECONOMIZER
COAL BUNKERS
FURNACE
COAL AND GAS BURNERS
TUBULAR AIR PREHEATER
COAL FEEDERS
PULVERIZERS
ASH HOPPER

Figure 21. Meramec unit no. 1. Union Electric Company.

The incoming refuse is shredded and air classified into heavy and light materials; see Figure 22. The light materials reportedly account for about 83 percent of the feed stream and consist of the light combustible with about 15 percent inert materials such as metal foil or sand.(103) The heavy material, consisting of the metals and inert material with about 25 percent combustible, is further separated to recover the ferrous and aluminum metals.

The light refuse material is pneumatically fed into the fluidized-bed combustor constructed of carbon steel lined with refractory brick and ceramic fiber insulation. In the combustor, the refuse contacts suspended sand particles which serve as a heat transfer medium to quickly heat the incoming refuse to the ignition temperature of 810 to 1000 C (1500-1800 F). To improve the electrical energy recovery the combustion reaction is conducted at a pressure of 3.5 atmospheres (37 psig); higher pressures, of 8.7 atmospheres (130 psig), have been recommended for a prototype installation.(103)

The exhaust stream from the fluid bed contains particles of sand, ash, particulates, and a small fraction of molten aluminum. The cleanup stage is very critical for the correct operation of the turbine electric generator. To prevent erosion of the turbine blades the minimum particle size entering the turbine should be considerably less than 5 microns. The initial separation is done in a large cyclone separator to remove the larger particles. The second and third cyclone separators are designed to remove smaller particles and ash.

The gases exiting the third cyclone separator are directed into the two-stage turbine-compressor and electric power generator. The gas expanding in the first turbine drives a compressor which provides the pressurized air for the fluidized bed combustor. The second turbine generates approximately 1 mw of electrical power.

This system is a relatively unique concept in waste-to-energy conversion. The front end processing system and electrical generating concept can recover marketable materials and produce saleable electricity.

The system, however, has been hampered with solids separation problems. The cyclone separators have proven to be inadequate for removing all of the small molten aluminum particles, resulting in deposits of aluminum oxide on the downstream turbine blades. A granular filter has been installed in an effort to alleviate this problem; the success of the new filter is not known as yet. The heterogeneous refuse fuel is also regarded as being a potential problem as it may interfere with the fluid nature of the bed. If proper velocities and temperatures are not maintained, large "chunks" may be formed, possibly resulting in a plugged bed.

The idea of generating electrical power on site is highly cost intensive and requires a balanced operation between two unrelated operations - disposal of refuse and the generation of electric power. The concept has yet to be satisfactorily proven, even on the pilot plant scale.

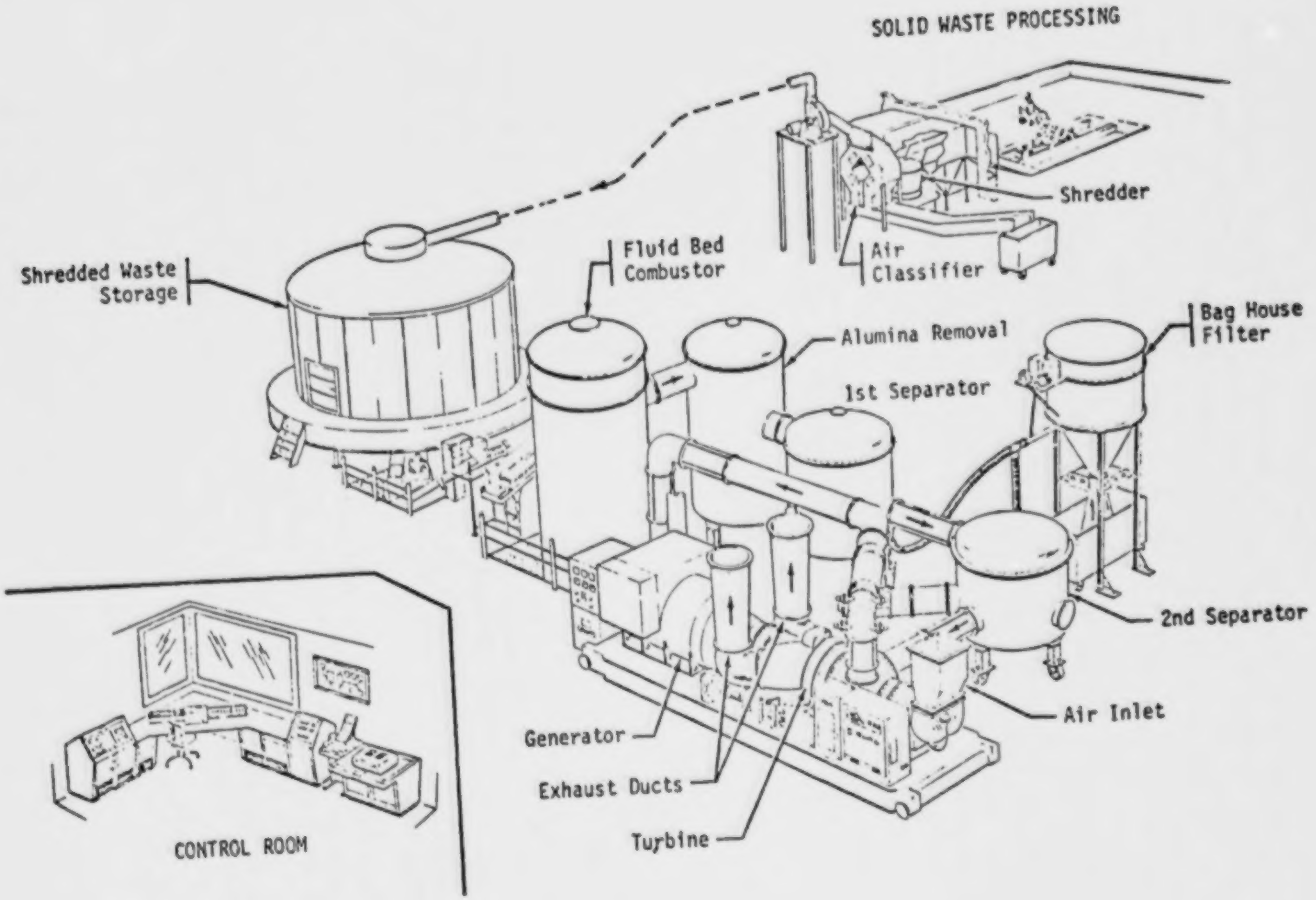

SOLID WASTE PROCESSING
Shredder
Air Classifier
Shredded Waste Storage
Fluid Bed Combustor
Alumina Removal
Bag House Filter
1st Separator
2nd Separator
Air Inlet
Generator
Exhaust Ducts
Turbine
CONTROL ROOM

Figure 22. CPU-400 pilot plant.

Pyrolysis

Introduction--

Pyrolysis has been defined as the physical and chemical decomposition of organic matter brought about by the action of heat in an oxygen-free or low-oxygen atmosphere.(108) This method of thermal decomposition has also been referred to as partial oxidation or destructive distillation depending on the method by which heat is supplied and the nature of the organic feed; in this report, all of these processes are regarded as pyrolysis.

In recent years, there has been an increasing interest in applying pyrolysis to solid organic wastes (biomass) principally to: (1) reduce the volume of wastes requiring disposal in an environmentally suitable manner; and, (2) to transform the organic waste into an alternate, easily usable energy form. As a result, several systems have been developed utilizing pyrolysis as one reaction in a multistep process, the entire process being typically referred to as "pyrolysis".

Development Status--

Pyrolysis has been applied to a wide variety of biomass waste. Some of the wastes on which experimental or more advanced pyrolysis evaluations have been conducted are as follows.

- Municipal/industrial solid waste
- Wood waste
- Agricultural waste
- Livestock waste
- Tires and rubber
- Energy crops
- Sewage

Most of the research on pyrolysis has been directed toward processing municipal solid waste. These processes are not well developed as yet; at present, there are only about 10-12 different systems in various stages of development.(108,109) Of these, 2 commercial size systems are onstream and 2 more are under construction; the remaining systems are either in the pilot plant or bench scale stages.

Chemical Reactions and Product Distribution--

Pyrolysis involves a complex process of simultaneous and consecutive endothermic chemical reactions. In pyrolysis, the heat causes the organic material to break down into smaller, simpler organic compounds yielding carbon monoxide, hydrogen, carbon dioxide, methane, and various hydrocarbons. Two of the principal reactions that occur during pyrolysis are described below.

$$C + H_2O + \text{heat} \longrightarrow H_2 + CO$$

$$C + CO_2 + \text{heat} \longrightarrow 2CO$$

The reactive portion of the solid waste is composed primarily of cellulosic material. The decomposition of this material occurs in a temperature range of 180 C (360 F) to 1600 C (3000 F)(110) producing a mixture of solid, liquid, and gaseous fuels, the compositions and proportions depending on the operating conditions. Some of the fuels are of sufficient quality that they may be blended with or substituted for conventional fossil fuels; others are of lower quality and are amenable to on-site use for the production of steam or electricity. Typical heating values for the by-products are 900 to 5400 kcal/m^3 (100 to 600 Btu/scf) for gases, 5600 to 6200 kcal/kg (10,000 - 11,000 Btu/lb) for solid char, and 3400 to 5000 kcal/kg (6000 - 9000 Btu/lb) for liquids.

Reactor Types--

Primarily three basic reactor types have been used for pyrolysis reactions: shaft, rotary kiln, and fluidized-bed. The shaft reactor may be either horizontal or vertical and is the simplest of the three reactor types; it is also the least capital intensive. In the horizontal type, the solid waste is continuously fed into the reactor on a conveyor system (mechanical, molten bed, etc.) where it is pyrolyzed to the solid, liquid, and gaseous products. In the vertical reactor, the solid waste is fed into the top and settles under its own weight. The produced gases diffuse up through the reactor and discharge out the top. The solid waste is typically fed by screw conveyors, rotary devices, and rams. The vessels are either lined with a refractory material or metal capable of withstanding the high reaction temperature, 180 - 1650 C (360 - 3000 F).

The rotary kiln consists of a metal rotary cylinder installed on bearings and inclined slightly to the horizontal. The feed waste is introduced into the upper end of the kiln and by rotation and gravity progresses to the lower end where it is discharged. The metal cylinder is usually lined with refractory brick. The rotation of the reactor provides mixing advantages over the shaft reactor but makes sealing of the feed and discharge ports a problem.

In the fluidized-bed reactor, the solid waste is introduced into a vessel and is contacted by solid particles (e.g., sand) suspended by an upward flowing gas stream. The solid particles, which may be heated in the same vessel or an external vessel, provide the heat of pyrolysis. The fluidized-bed reactor offers improved heat transfer and temperature control over the other reactor types but suffers from erosion, entrainment of solid particles, and gas velocity control.

Heating Methods--

There are 2 distinct methods of providing heat for the endothermic pyrolysis reaction, direct and indirect. In this study, the direct method is defined as the partial combustion of the waste and/or supplementary fuel within the pyrolysis reactor to provide the heat of reaction. In direct heating the combustion reaction consumes oxygen and generates CO_2 and H_2O which dilute the product gas resulting in a reduced heating value. The use of air as a source of oxygen further dilutes the gas with the large amounts of N_2 and when burned can cause potential environmental problems as a result of NO_x formation.

In the indirect method, the pyrolysis zone is separated from the heat source. The separation may be accomplished by the use of a heat conduction barrier (wall) or a separate heat transfer medium (e.g., sand, char, molten bed). For solid waste pyrolysis applications the barrier or wall is not as attractive as the separate heat transfer medium due to corrosion problems and the larger heat resistances of the refractory linings and slag coatings. The separate heat transfer medium, however, suffers from solids transfer and separation problems. In summary, indirect methods generate a less diluted gaseous by-product but are generally less efficient than direct methods. The general characteristics and methods of heating used by the different reactor types are listed in Table 40.

Process Variables--

The major parameters affecting the product yields and composition are the temperature, residence time/heating rate, and waste feed conditions.(111) At low reaction temperatures, the products are heavier in molecular weight, the ratio of gases and liquids to solids is relatively low, and the gases that are generated contain higher molecular weight molecules. As the reaction temperature increases, more cracking occurs forming more lighter weight gases richer in hydrogen. This trend is illustrated in Table 41. The gaseous product mix obtained from the pyrolysis of municipal solid waste from which glass and metal components had been previously removed is shown in Table 41. The composition of the pyrolysis gas is shown in Table 42.

TABLE 40. REACTOR TYPE CHARACTERISTICS (110,111)

			Indirect Heating			
	Direct Heating		Wall Transfer		Circ. Medium	
Type of Reactor	Operational Simplicity	Heating Rate	Operational Simplicity	High Heating Rate	Operational Simplicity	High Heating Rate
Vertical Shaft	+		+	-	-	+
Horizontal Shaft	NONE	NONE	-	-	-	+
Rotary Kiln	+		+	-	-	+
Fluidized Bed	-	+	NONE	NONE	-	+

Note: 1. A plus (+) entry indicates a virtue while a minus (-) entry indicates a detriment.

2. A NONE entry indicates that no process development has been reported in that category.

3. No entry implies neither a virtue nor a detriment.

TABLE 41. INFLUENCE OF TEMPERATURE ON PYROLYSIS PRODUCTS(112)

Temperature C	Products, wt percent			Mass Balance percent	Gases Produced per .454 kilograms (1 lb) of Combustibles		
	Gases	Pyroligneous Acids & Tars	Char		m^3 (cu ft)(a)	kcal/m^3 (Btu/cu ft)	kcal/kg (Btu/lb)
500	12.3	61.1	24.7	98.1	0.05 (1.9)	2700 (300)	320 (570)
650	18.6	59.2	21.8	99.6	0.08 (2.78)	3380 (376)	580 (1045)
800	23.7	59.7	17.2	100.6	0.10 (3.62)	3100 (344)	690 (1245)
900	24.4	58.7	17.7	100.7	0.09 (3.39)	3160 (351)	660 (1190)
750	23.7	57.1	11.5	92.3	0.14 (4.84)	4170 (463)	1500 (2700)
900	39.5	48.0	7.7	95.2	0.25 (8.90)	4020 (447)	2220 (3990)

(a) At 1 atmosphere and 21 C.

TABLE 42. COMPOSITION OF PYROLYSIS GAS(112)

Constituent	Gas Produced, percent					
	500 C	650 C	800 C	900 C	750 C	900 C
Hydrogen	5.56	16.6	28.6	32.5	30.9	51.9
Methane	12.4	15.9	13.7	10.5	22.6	12.7
Carbon monoxide	33.5	30.5	34.1	35.3	15.6	18.2
Carbon dioxide	44.8	31.8	20.6	18.3	18.4	11.4
Ethylene	0.45	2.18	2.24	2.43	7.56	0.14
Ethane	3.03	3.06	0.77	1.07	2.05	0.14

The residence time and rate of heating also affect the yields of gas, liquid, and char. Table 43 shows the products obtained from the pyrolysis of newspaper at various heating rates.(112) As can be seen, the char and gas yields increased with a decreased heating rate and the yield of organic liquid showed a general increase with heating rate.

Some pyrolysis reactors have been designed to accommodate specific waste feed conditions while others are more flexible and operate with a variety of waste fuel conditions. The flexibility of a process is usually determined by the reactor type, operating conditions, and inorganic product utilization considerations. The more selective processes will usually require preprocessing of some form or another, e.g., shredding, drying, separation, etc. Preprocessing, however, is generally desirable regardless of whether the process requires it.

One feed condition that can influence the yield of the various products is the moisture content. A study was conducted by the Bureau of Mines on the effects of moisture content in solid municipal waste on the product yields and composition.(113) It was discovered that the presence or absence of moisture in the feed can significantly alter the product distribution. At the pyrolysis temperatures, the water-gas-shift, the steam-carbon, and the steam-hydrocarbon reactions all proceed rapidly.

$$H_2O + CO \rightarrow CO_2 + H_2$$

$$H_2O + C \rightarrow CO + H_2$$

$$H_2O + CH_4 \rightarrow CO + 3H_2$$

Large quantities of moisture will shift the equilibrium of the above reactions to the right. This trend is illustrated in Table 44, a summary of experimental results on refuse pyrolyzed at 900 C (1620 F).(113)

Description of Processes--

Table 45 presents a summary of the more significant pyrolysis processes highlighting some of the major design and operating classifications. An "x" entry indicates that the process qualifies for the specific classification, no entry means that the process does not qualify for the classification, and an "N.A." means that the information is not available. Each of the tabulated processes is addressed in more detail in the following discussions.

Vertical Shaft Reactors--

Five vertical shaft reactor processes were selected for examination.

Garrett process--The Garrett Research and Development Company (recently merged into its parent company, Occidental Petroleum Corporation) has modified a coal conversion process to convert municipal refuse and other wastes into synthetic fuel oil for possible use as a substitute for No. 6 fuel oil. The process has been tested on a 3.6 metric tons per day (4 tons per day) pilot plant over an 18-month period and construction has been completed on a 180 metric tons per day (200 tons per day) EPA-funded demonstration plant in San Diego.(110)

TABLE 43. PRODUCTS FROM PYROLYSIS OF NEWSPAPER[112]

Constituents	Yields, wt percent								
Minutes to 800C →	1	6	10	21	30	40	60	60	71
Gas	36.3	27.1	24.8	23.5	24.3	24.1	25.3	29.6	31.1
Water	24.1	27.4	27.4	28.2	27.9	27.1	33.2	30.7	28.3
Organic liquids	19.1	25.6	25.7	26.2	24.5	24.8	12.0	9.93	10.7
Char	19.1	18.6	20.7	20.6	21.9	22.5	28.1	28.1	28.5
Ash	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43
Kcal(Btu) in gas per .454 kg (1 lb) newspaper	500 (2,000)	350 (1,400)	300 (1,200)	275 (1,100)	300 (1,200)	275 (1,100)	325 (1,300)	425 (1,700)	400 (1,600)

TABLE 44. PYROLYSIS OF DRIED REFUSE AT 900 C(113)

Characteristic	High Moisture Refuse	Low Moisture Refuse
Moisture in feed, wt percent	43.3	7.3
Yields per 0.9 MT (1 Ton) of feed		
Gas, cu meters (SCF)	496 (17,741)	517 (18,470)
Oil, liters (gal)	1.8 (0.5)	61.2 (16.2)
Ammonium sulfate, kg (lb)	11.2 (25.1)	16.9 (37.5)
Aqueous, liters (gal)	427 (114)	127 (34.1)
Gas Composition, vol percent		
CO_2	11.4	9.1
CO	18.1	23.0
H_2	51.9	37.8
CH_4	12.7	24.4
C_2 and heavier	5.9	5.7
Heating value, kcal/m^3 (Btu/cu ft)	4040 (447)	4910 (545)
Heat available million kcal/MT[a] (million Btu/T)		
Feed	2.21 (9.65)	4.06 (17.78)
Gas	1.81 (7.93)	2.30 (10.07)

(a) Metric ton.

TABLE 45. PYROLYSIS AND PARTIAL OXIDATION CLASSIFICATIONS

Process Name	Process Type	Feed Characteristics					Method of Heating	Reactor	Maximum Reactor Temperature °C (°F)	Reactor Pressure (Atm Absolute)
		Feed Types	Raw	Size Reduction	Separation	Drying				
Garrett	Pyrolysis	MSW, sewage agricultural and feed lot wastes, tires		X	X	X	Indirect	Vertical shaft	482 (900)	1
Battelle	Partial oxidation	MSW *		X			Direct	Vertical fixed bed	1090(2000)	1
TORRAX	Partial oxidation	MSW					Direct	Vertical fixed bed	1650(3000)	1
Union Carbide Purox	Partial oxidation	MSW		X	X		Direct	Vertical fixed bed	1650(3000)	1
Georgia Tech	Partial oxidation	Agricultural & forest wastes		X		X	Direct	Vertical shaft	400-500 (750-930)	1
Barber-Colman	Pyrolysis	MSW		X	X		Indirect	Horizontal shaft	650 (1200)	
Monsanto Land Gard	Partial oxidation	MSW, sewage waste, tires		X			Direct	Horizontal rotary kiln	1090(2000)	1
DEVCO	Partial oxidation	MSW		X	X		Direct	Horizontal rotary kiln	540(1000)	1
West Virginia	Pyrolysis	MSW		X	X	X	Indirect	Fluidized bed	815(1500)	1

* Municipal solid waste

TABLE 45. (Continued)

Process Name	Supple-mental Fuel Required	Product Distribution			Status		Other Resource Recovery Options
		Solid kcal/kg (Btu/lb)	Liquid kcal/kg (Btu/lb)	Gas kcal/m^3 (Btu/scf)	Pilot Plant Metric Tons Per Day (Ton Per Day)	Commercial Metric Tons Per Day (Ton Per Day)	
Garrett		5000 (9000)	5,500 (10,000)	4500-5400 (500-600)	3.6(4)	180 (200) Under construction	Glass, ferrous metals, aluminum
Battelle				900-1800 (100-200)	1.8(2)		None
TORRAX	X			1000 (110)	67 (75)		None
Union Carbide Purox				3150 (350)	4.5(5)	180 (200) Operating	Ferrous metals
Georgia Tech		6100-7200 (11,000-13,000)			23 (25)		None
Barber-Colman				4500-5400 (500-700)	0.7(.75)		Ferrous metals
Monsanto Land Gard	X	3800 (7000)		1080 (120)	32 (35)	900 (1000) Operating	Ferrous metals, glass
DEVCO	X	5,500 (10,000)		N.A.	6.3(7)	1350 (1500) Under construction	Metals
West Virginia				3600 (400)	< 1 (1)		

The process is schematically depicted in Figure 23. Incoming refuse is first shredded to a particle size of 2 inches or less. An air classifier then separates the light, organic fraction from the heavy, inorganic fraction. The organic fraction is dried in a rotary drier to above 3 percent moisture, screened to reduce the inorganic content to less than 4 percent, and further shredded to about 28 mesh size. The ferrous metals are magnetically reclaimed from the heavy inorganic fraction and sand-sized, mixed-color glass of 99.7 percent purity is recovered from the remaining inorganics.

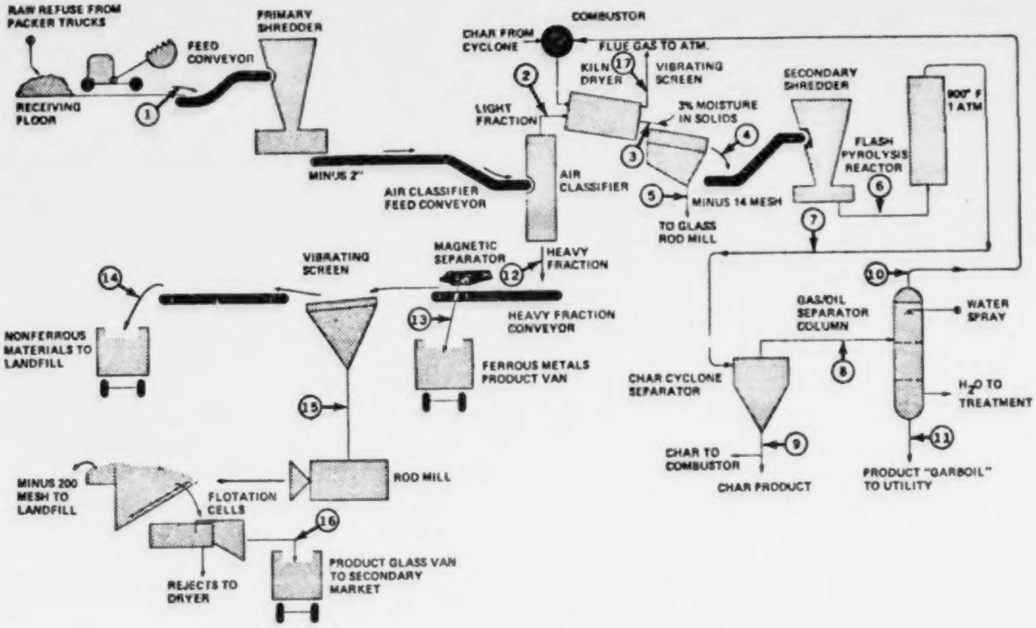
The organic material is fed to the base of the vertical shaft pyrolysis reactor where it is mixed with burning char (indirect heating). Both materials are conveyed into the reactor by the spent combustion gases from the drying combustor. In the reactor, the finely shredded organic waste and the hot char suspension rise upward and mix under turbulent flow conditions. At an operating temperature of 480 C (900 F), the organic material flash pyrolyzes into oil, gas, char, and water products. The entire suspension flows out of the top of the reactor into a cyclone separator, where the char is removed. A venturi quench system, operating with recovered oil, quickly cools the rich effluent product gas stream from 480 C (900 F) before extensive thermal cracking of the liquid constituents occurs. The outlet gas is cooled further to about 43 C (110 F) in a packed-bed scrubber before recycling to the combustor. The oil product separates from the cooling water and is withdrawn from the bottom of the scrubber.

Research was conducted on the pilot plant using a municipal solid waste feed; the product yields are shown in Table 46.(114)

The product gas, which accounts for about 27 weight percent of the products, is not intended for market sale and is consumed by the system to provide process heat. The comparatively rich gas has a heating value of 4500 to 5400 kcal/m^3 (500 to 600 Btu/scf). Based on pyrolyzing the municipal refuse, the gas is reported to have the following composition.

Component	Volume Percent
H_2	16.7
CH_4	15.4
CO	17.9
CO_2	23.1
C_2 hydrocarbons	22.2
C_3-C_7 hydrocarbons	4.7

Gas obtained from various agricultural products, however, is higher in CO_2 and lower in caloric value. Typical values range from 40 mole percent CO_2 and 2250 kcal/m^3 (250 Btu/scf) for rice hulls to 28 mole percent CO_2 and 3000 kcal/m^3 (330 Btu/scf) for grass straw. Table 47 shows the representative product yields obtained from laboratory experiments on other waste feeds.(114)


RAW REFUSE FROM PACKER TRUCKS
RECEIVING FLOOR
FEED CONVEYOR
PRIMARY SHREDDER
①
MINUS 2"
AIR CLASSIFIER FEED CONVEYOR
COMBUSTOR
CHAR FROM CYCLONE
FLUE GAS TO ATM.
②
LIGHT FRACTION
KILN DRYER
⑰
VIBRATING SCREEN
3% MOISTURE IN SOLIDS
③
④
AIR CLASSIFIER
⑤
MINUS 14 MESH
TO GLASS ROD MILL
SECONDARY SHREDDER
FLASH PYROLYSIS REACTOR
900° F 1 ATM
⑥
⑦
MAGNETIC SEPARATOR
HEAVY FRACTION
⑫
VIBRATING SCREEN
⑭
⑬
HEAVY FRACTION CONVEYOR
NONFERROUS MATERIALS TO LANDFILL
FERROUS METALS PRODUCT VAN
⑩
GAS/OIL SEPARATOR COLUMN
WATER SPRAY
⑧
CHAR CYCLONE SEPARATOR
H_2O TO TREATMENT
⑮
⑨
CHAR TO COMBUSTOR
CHAR PRODUCT
⑪
PRODUCT "GARBOIL" TO UTILITY
MINUS 200 MESH TO LANDFILL
FLOTATION CELLS
ROD MILL
⑯
REJECTS TO DRYER
PRODUCT GLASS VAN TO SECONDARY MARKET

STREAM NO.		COMPONENT	TONS/ DAY	TOTAL TONS/ DAY	TONS/ HR PER TRAIN
1	RAW REFUSE FEED	RAW REFUSE	1000	1000	* 1 & 2
2	LIGHT FRACTION TO DRYER	LIGHT FRACTION	775	775	
3	LIGHT FRACTION FROM DRYER	LIGHT FRACTION	775	775	
4	FEED TO SECONDARY SHREDDER	LIGHT FRACTION	754	754	
5	SCREENED GLASS FROM LIGHT FRACTION	GLASS, CERAMICS, ETC.	21	21	
6	FEED TO PYROLYSIS REACTOR	LIGHT FRACTION	754	754	
7	PYROLYSIS PRODUCTS TO CYCLONE SEPARATOR	CHAR OILS GASES	80 240 434	754	
8	OILS & GASES TO SEPARATOR COLUMN	OILS GASES	240 434	674	
9	CHAR FROM PYROLYSIS PRODUCTS	CHAR	80	80	
10	PYROLYSIS GASES TO REACTOR	GASES	157	157	

STREAM NO.		COMPONENT	TONS/ DAY	TOTAL TONS/ DAY	TONS/ HR PER TRAIN
11	PRODUCT PYROLYSIS OIL	OILS	240	240	
12	HEAVY FRACTION FROM AIR CLASSIFIER	HEAVY FRACTION	225	225	
13	FERROUS METALS FROM MAGNETIC SEPARATOR	FERROUS METALS	70	70	
14	NONFERROUS MATERIALS TO LANDFILL	NONFERROUS MATERIALS	55	55	
15	SCREENED GLASS, CERAMICS TO ROD MILL	GLASS, CERAMICS, ETC.	100	100	
16	PRODUCT GLASS FROM FLOTATION CELLS	GLASS PRODUCT	82	82	
17	WATER REMOVED FROM LIGHT FRACTION	WATER	277	277	

*1 FRONT END SYSTEM THROUGH SECONDARY SHREDDER OPERATE 10 HOURS/DAY, 5 DAYS/WEEK. TWO TRAINS REQUIRED.

*2 PYROLYSIS SECTION WOULD OPERATE 24 HOURS/DAY, 7 DAYS/WEEK.

LARGEST MODULE SIZE NOT RELEASED BY GARRETT.

Figure 23. Flow schematic of Garrett pyrolysis process.(110)

TABLE 46. TYPICAL PRODUCTS OF PYROLYSIS(a)(114)

Char fraction (20 wt percent), heating value 5000 kcal/kg (9000 Btu/lb)	
48.8(b)	Carbon
3.9	Hydrogen
1.1	Nitrogen
0.3	Sulfur
31.8	Ash
0.2	Chlorine
13.9	Oxygen (by difference)
Oil fraction (40 wt percent), heating value 5800 kcal/kg (10,500 Btu/lb)	
57.5	Carbon
7.6	Hydrogen
0.9	Nitrogen
0.1	Sulfur
0.2	Ash
0.3	Chlorine
33.4	Oxygen (by difference)
Gas fraction (27 wt percent), heating value 5000 kcal/m^3 (550 Btu/scf)	
0.1(c)	Water
42.0	Carbon monoxide
27.0	Carbon dioxide
10.5	Hydrogen
<0.1	Methyl chloride
5.9	Methane
4.5	Ethane
8.9	C_3-C_7 hydrocarbons
Water fraction (13 wt percent)	
Contains	Acetaldehyde
	Acetone
	Formic acid
	Furfural
	Methanol
	Methylfurfural
	Phenol
	Etc.

(a) Shredded municipal refuse with about 90 percent of the inorganics removed was supplied by the Black Clawson Company of Middletown, Ohio. Product yields are based upon oven-dried feed, pyrolyzed at about 500 C at atmospheric pressure without hydrogenation.

(b) In units of wt percent

(c) In units of mole percent

TABLE 47. AVERAGE YIELDS OF PYROLYSIS PRODUCTS FROM DOUGLAS FIR BARK, RICE HULLS, GRASS STRAW, AND COW MANURE (114)

Material	Weight percentage of dry feed			
	Oil	Char	Gas	Water
Douglas fir bark	35-50	50-25	5-15	10
Rice hulls	40	35	10	15
Grass straw	50	20	15	5
Cow manure	30	45	15	10

The char accounts for about 20 weight percent of the products from municipal waste pyrolysis and has a heating value of about 5000 kcal/kg (9000 Btu/lb). A representative analysis of the char, based on pyrolyzing municipal waste, is presented as follows.

Component	Weight Percent
Carbon	48.8
Hydrogen	3.9
Nitrogen	1.1
Sulfur	0.3
Ash	31.8
Chlorine	0.2
Oxygen (by difference)	13.9

Approximately 2/3 of the produced char is burned as fuel for process heat.(114) No marketable value has been assigned to the remainder of the char except perhaps as a solid fuel.

The liquid fuel obtained from the solid municipal waste pyrolysis reaction accounts for about 40 weight percent of the products. It is a complex, highly oxygenated organic fluid, lower in both carbon and hydrogen than No. 6 fuel oil (see Table 48). The heat value of the pyrolysis oil is about 5800 kcal/kg (10,500 Btu/lb) as compared to 10,000 kcal/kg (18,200 Btu/lb) for typical No. 6 fuel oil. The fuel oil is also more viscous than No. 6 fuel oil and at temperatures above 93 C (200 F) is thermally unstable and will undergo changes which further increase its viscosity. The fuel oil is also slightly acidic and will corrode mild steel at 93 C (200 F). Proper blending of the pyrolysis fuel with No. 6 fuel oil, however, is reported to result in a thermally stable, noncorrosive mixture which may be successfully

TABLE 48. TYPICAL PROPERTIES OF NO. 6 FUEL OIL AND PYROLYTIC OIL (114)

Property	No. 6 oil	Pyrolytic oil
Carbon (wt percent)	85.7	57.5
Hydrogen (wt percent)	10.5	7.6
Sulfur (wt percent)	0.5-3.5	0.1-0.3
Chlorine (wt percent)		0.3
Ash (wt percent)	<0.5	0.2-0.4
Nitrogen (wt percent)	2.0	0.9
Oxygen (wt percent)		33.4
kcal/kg (Btu/lb)	10,000 (18,200)	5,800 (10,500)
Specific gravity	0.98	1.30
Pour point C (F)	18-29 (65-85)	32 (90)
Flash point C (F)	66 (150)	56 (133)
Viscosity (SSU at 88 C)	90-250	1000
Pumping temperature C (F)	46 (115)	71 (160)
Atomization temperature C (F)	104 (220)	115 (240)

burned in utility boilers with properly designed fuels handling and automization systems.

Based on the pilot plant results, the Garrett Process will produce approximately 1 bbl of oil, 64 kg (140 lb) of magnetic metals, 55 kg (120 lb) of glass, 73 kg (160 lb) of char, and 146 kg (320 lb) of landfill material from 0.9 metric ton (1 ton) of municipal solid waste.

As can be seen from Table 46, the produced water accounts for about 13 percent of the products. The water contains alcohol and other oxygenated hydrocarbons and has a high BOD. It was stipulated, however, that the water would present no disposal problem provided secondary sewage facilities are available.(114)

Other pyrolysis tests have been conducted on cow manure. The oxygen content of the oil was lower and the average caloric value was about 560 kcal/kg (1000 Btu/lb) higher than oil from municipal waste. However, in view of the restrictions being placed on NO_x emissions, the high nitrogen content of the oil (5 - 7 weight percent) was believed to make it an unattractive boiler feed.(114)

The various advantages and disadvantages cited for the Garrett Process are listed below.

Advantages

- Production of low sulfur fuel oil possibly adaptable to utility boilers
- Process adaptable to a variety of waste feeds
- No auxiliary fuel required
- Recovery of other resources, aluminum, glass and ferrous metals

Disadvantages

- Corrosive and unstable nature of fuel oil
- Relatively extensive preprocessing of waste feed required
- Large-scale tests of oil in boilers not yet started
- Low net thermal efficiency about 45 percent(109)

Battelle pyrolysis process--Battelle-Northwest developed a pyrolysis process in which solid waste is progressively dried, pyrolyzed, and finally oxidized by an air/steam mixture to produce a low Btu fuel gas. The process was evaluated on municipal waste and wood chips in the early 1970's on a 3 to 5 ton per day pilot plant at Richland, Washington.(115)

The system utilized a vertical shaft reactor (Figure 24) into the top of which is dumped shredded solid refuse or waste. Air and steam are injected into the combustion zone at the bottom of the reactor. The hot combustion gases rising up through the descending waste provide the heat for hydrogen production and drying and generate a low Btu fuel gas. The fuel gas, based on the pyrolysis of MSW, has a heating value of 900 to 1800 kcal/m^3 (100 to 200 Btu/scf), or about 80 percent of the energy charged to the system. A typical analysis of the gas is shown below.(115)

Component	Mole Percent (dry basis)
H_2	21.6
CO	21.0
CH_4	1.8
C_2H_5	0.15
C_2H_4	0.27
O_2	trace
N_2	43.3
CO_2	11.8
	100.0

The slagged wastes tapped from the reactor bottom are quenched and disposed of in a landfill.

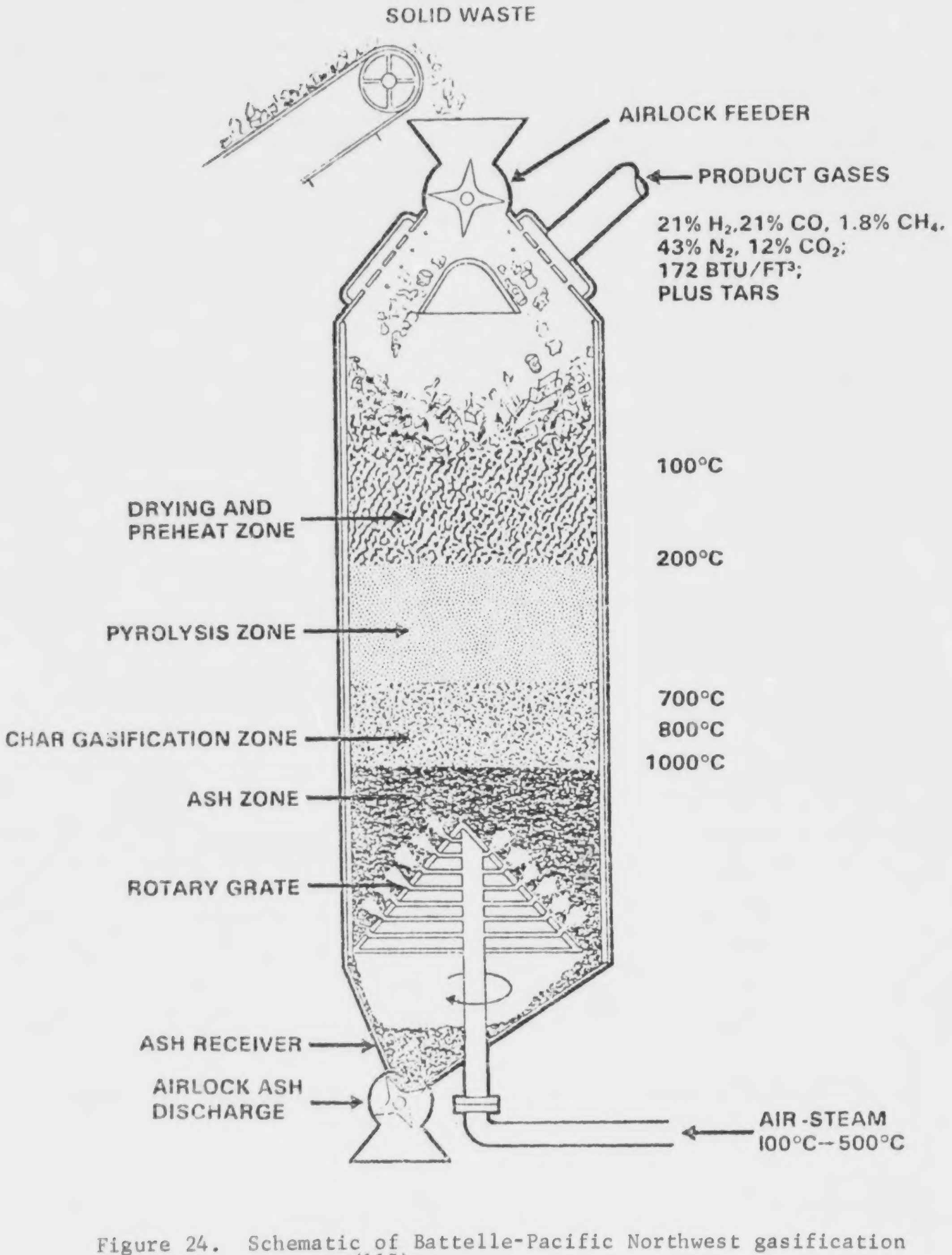

SOLID WASTE
AIRLOCK FEEDER
PRODUCT GASES
21% H_2, 21% CO, 1.8% CH_4,
43% N_2, 12% CO_2;
172 BTU/FT³;
PLUS TARS
100°C
DRYING AND PREHEAT ZONE
200°C
PYROLYSIS ZONE
700°C
800°C
1000°C
CHAR GASIFICATION ZONE
ASH ZONE
ROTARY GRATE
ASH RECEIVER
AIRLOCK ASH DISCHARGE
AIR-STEAM
100°C–500°C

Figure 24. Schematic of Battelle-Pacific Northwest gasification process.(115)

Two advantages cited for the process are its versatility and apparent ability to process unsegregated refuse and its high thermal efficiency. The major disadvantage is the production of a low Btu, nonstorable fuel gas.

Torrax process--The Torrax pyrolysis process was developed by Carborundum Environmental Systems, Inc., and was demonstrated from 1969 through the early 1970's on a 68 metric tons per day (75 tons per day) pilot plant in Erie County, New York. The process burns natural gas for preheating air to 1100 C (2000 F) to help induce pyrolysis and achieve the high slagging temperature in the combustion zone. Although designed to convert energy from refuse to steam, the process can also be altered to produce a low-Btu fuel gas. Andco-Torrax is the present process developer; they have constructed several units for European operation.

A simplified schematic of the process is shown in Figure 25. Unsorted refuse is periodically charged without pretreatment into the top of the vertical shaft reactor. Air, preheated to 1090 C (2000 F) by passing through a natural gas or oil-fired blast superheater, is introduced into the bottom of the reactor. Natural gas heat requirements average about 250,000 kcal/metric ton (1 million Btu/ton) of municipal waste. The air provides the oxygen and heat to maintain the temperature at the base of the reactor at 2600 - 3000 F. As the refuse slowly descends in the reactor, the hot gases permeating up through the refuse decompose the more readily combustible materials to form the pyrolysis gas. The gas leaves the gasifier at a temperature of 480 - 540 C (900 - 1000 F) and passes into an ignitor where it is combusted to produce steam. The gas has a heat value ranging between 910 and 1350 kcal/m^3 (110 and 150 Btu/scf) and a composition typical to that shown below. The supplier estimates that an energy content of 57,300 kcal/metric ton (7.6 million Btu/ton) of MSW feed can be recovered from the fuel gas.(109)

Component	Mole Percent (dry basis)
Carbon dioxide	9.9
Nitrogen	64.5
Oxygen	5.0
Carbon monoxide	9.5
Hydrogen	10.8
Methane	1.4
Ethane	0.2
Propane	0.13

The molten slag produced in the reactor ignitor is tapped and fritted to produce a glassy aggregate. No marketable value was assigned to the aggregate.

Union Carbide Purox process--The Linde Division of the Union Carbide Corporation has developed a slagging temperature pyrolysis system (Purox System) which utilizes oxygen for the combustion of pyrolysis char to produce a fuel gas for off-site use. The original pilot plant work was conducted on a 4.5 metric tons per day (5 tons per day) reactor in Tarrytown, New York,

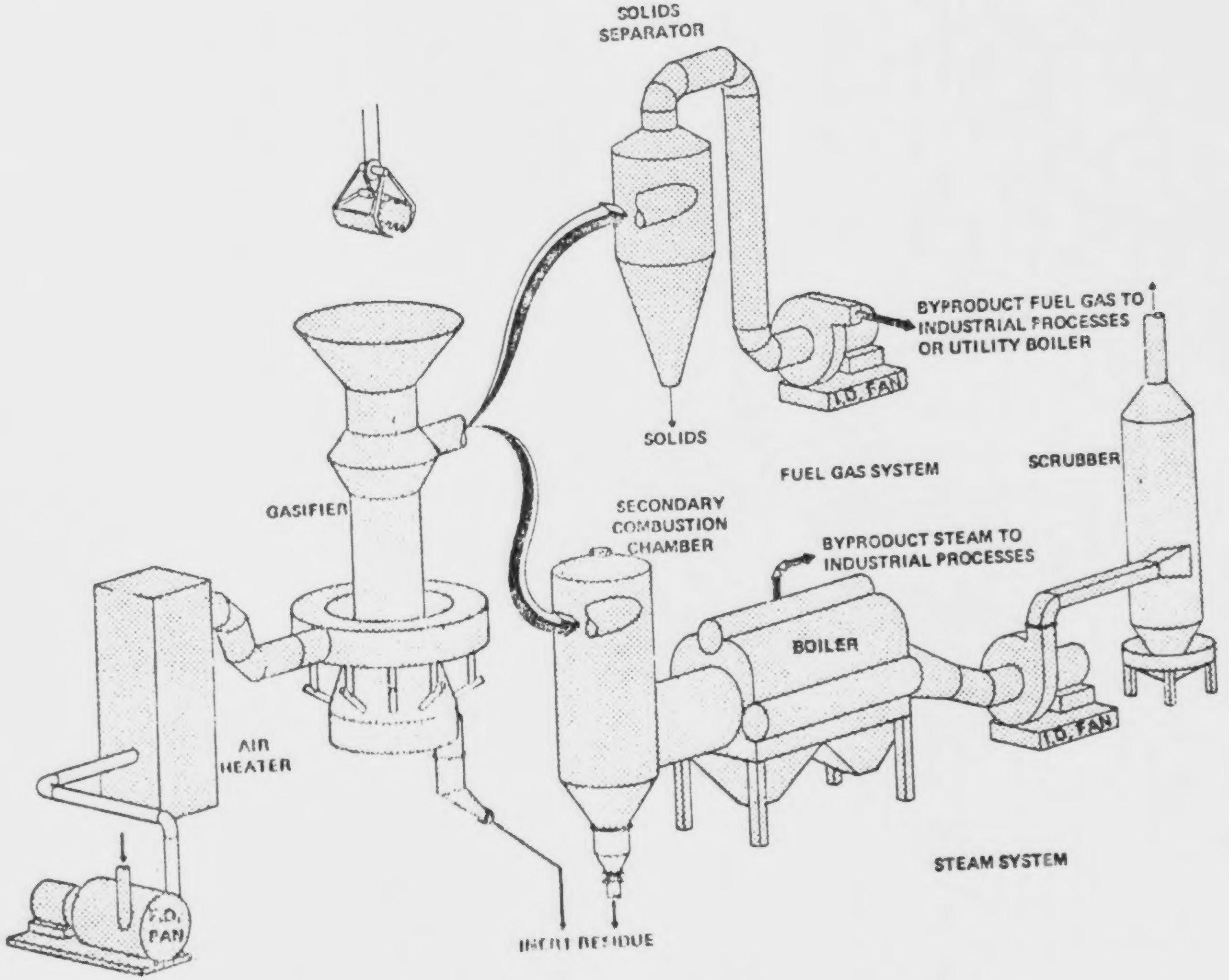

SOLIDS SEPARATOR
BYPRODUCT FUEL GAS TO INDUSTRIAL PROCESSES OR UTILITY BOILER
I.D. FAN
SOLIDS
FUEL GAS SYSTEM
SCRUBBER
GASIFIER
SECONDARY COMBUSTION CHAMBER
BYPRODUCT STEAM TO INDUSTRIAL PROCESSES
BOILER
I.D. FAN
AIR HEATER
F.D. FAN
INERT RESIDUE
STEAM SYSTEM

Figure 25. Carborundum Environmental Systems, Incorporated - Torrax process.

and a full-scale 180 metric tons per day (200 tons per day) demonstration plant, funded by Union Carbide, has been operating since April, 1974, in South Charleston, West Virginia.

Figure 26 depicts the flow diagram of the Purox Process. The waste feed is initially shredded to nominal 15 cm x 15 cm (6 in. x 6 in.) size particles after which the ferrous metals are removed in a magnetic separator. The remaining feedstock, consisting primarily of organic wastes and gas, is fed by a ram feeder into the side of the vertical shaft furnace. Oxygen, at a rate of approximately 0.18 metric ton (0.2 ton) per ton of solid waste, is injected into the base of the solid waste column where it reacts with the char (the solid residue remaining after the pyrolysis of the waste). The 1650 C (3000 F) bed temperature is sufficient to melt or slag the inorganic residue (metal and glass) which continuously drains into a water quench tank where it coalesces to form a hard, granular material. Essentially all of the drying, pyrolysis, and combustion of the waste occurs in the lower 0.9 meter (3 feet) of the reactor where the temperature ranges from 1650 C (3000 F) at the base of the reactor to 120 C (240 F) at the 0.9 meter (3 foot) level.(110)

The hot combustion gases rising up through the descending solid waste provide the heat for pyrolysis and drying. The gas exhausting from the shaft furnace contains some water vapor and oil mist and minor undesirable components. These components are removed by a gas cleanup train consisting of a water scrubber and an electrostatic precipitator. The removed materials are disposed of by recirculating to the furnace.

The use of oxygen, rather than air, for promoting the combustion yields a more concentrated gas fuel with a heating value of about 3200 kcal/m^3 (350 Btu/scf). A constituent analysis of the gas resulting from the pyrolysis of municipal solid waste is presented in Table 49.(116) The gas is essentially free of sulfur and has combustion characteristics similar to natural gas; for this reason, it is suggested that the gas either be substituted for natural gas in modified gas boilers or upgraded to pipeline quality and sold as natural gas. Due to the high hydrogen and carbon monoxide content, Union Carbide also suggests that the gas may be useful for synthesis of ammonia, methanol, or oxygenated organic chemicals.(116)

The major limitation on the use of the gas is the extra cost of compressing it for storage and shipment. Three times more energy will be required to compress the pyrolysis gas than to compress natural gas. As a result, Union Carbide suggests that the market for the pyrolysis gas not be more than 1 or 2 miles from the producing facility.(116)

The slagged reactor bottoms are comprised primarily of glass and aluminum. Table 50 presents an analysis of the residue.(116) The residue is claimed to be useful as a construction aggregate.

The only waste stream is the water condensed from the product gas at a rate of about 80 gallons per ton of refuse. The stream, which is high in BOD, may be reduced to acceptable limits (200 to 300 BOD) by existing technology before discharge to a municipal sewer.

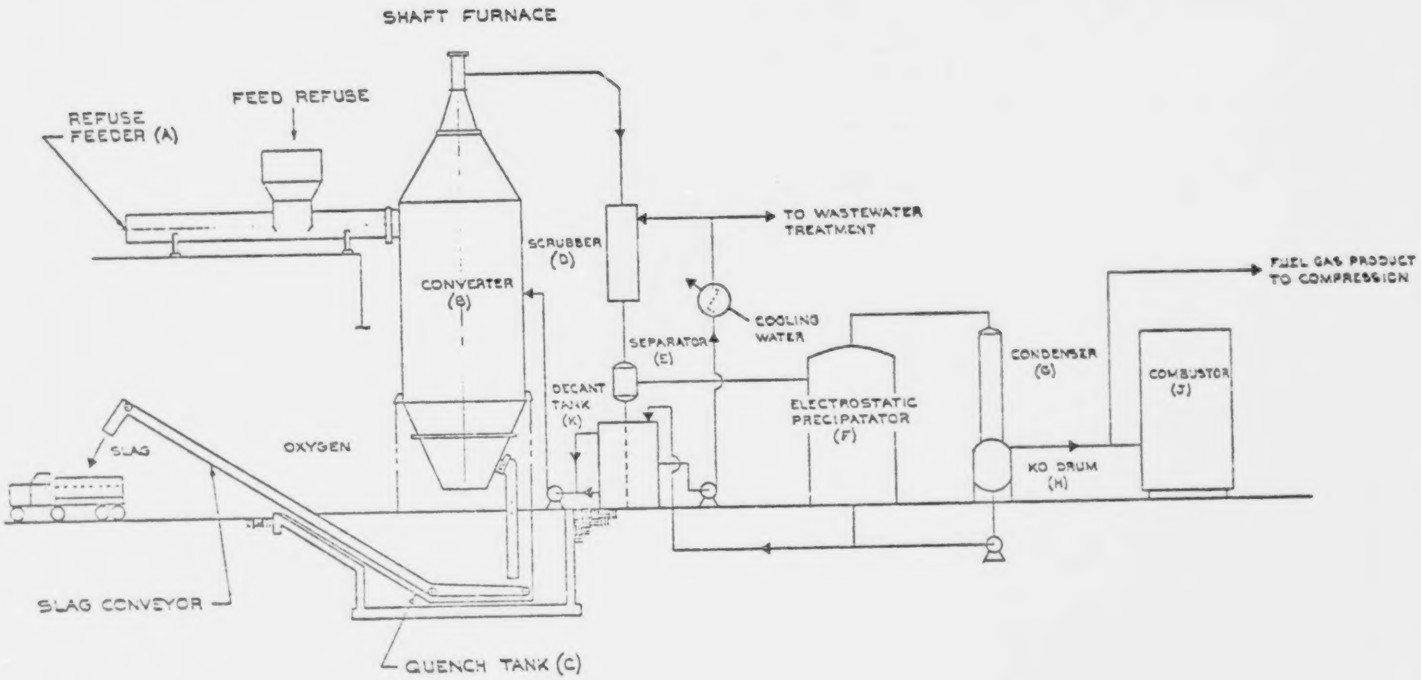

SHAFT FURNACE
FEED REFUSE
REFUSE FEEDER (A)
CONVERTER (B)
SCRUBBER (D)
TO WASTEWATER TREATMENT
COOLING WATER
SEPARATOR (E)
DECANT TANK (K)
ELECTROSTATIC PRECIPATATOR (F)
CONDENSER (G)
KO DRUM (H)
COMBUSTOR (J)
FUEL GAS PRODUCT TO COMPRESSION
SLAG
OXYGEN
SLAG CONVEYOR
QUENCH TANK (C)

Figure 26. Union Carbide Purox process.(116)

TABLE 49. PUROX SYSTEM PRODUCT GAS ANALYSIS(116)

Component	Volume Percent - Dry Basis Typical	Volume Percent - Dry Basis Range
H_2	24	21-31
CO	40	38-42
CO_2	25	20-26
CH_4	5.6	4-7
C_2H_2	0.7	0.4-1.1
C_2H_4	2.1	1-3
C_2H_6	0.3	0.2-0.4
C_3H_6	0.3	0.2-0.4
C_3H_8	0.2	0.1-0.3
C_4	0.5	0.3-0.6
C_5	0.4	0.2-0.5
C_6H_6	0.3	0.2-0.5
C_7H_8	0.1	0.05-0.15
C_6^+	0.2	0.1-0.7
H_2S	0.05	0.02-0.06
CH_3OH	0.1	0.5-0.15
Organic Vapors (a)	0.15	0.05-0.3
Heating Value, Dry Basis, kcal/m^3 (Btu/scf)		
Higher	3330 (370)	2700-2100 (300-390)
Lower	3100 (345)	2520-3240 (280-360)

(a) Higher alcohols, aldehydes, ketones, and organic acids.

TABLE 50. PUROX SYSTEM RESIDUE ANALYSIS(116)

Component	Weight Percent, Expressed as Oxide	
Slag Fraction - 97 Percent of Total Residue		
	Typical	Range
Silicon	59.7	57-62
Aluminum	10.5	9-13
Calcium	10.3	9-12
Sodium	8.0	7-10
Iron	6.2	1-8
Magnesium	2.2	1-4
Potassium	1.0	
Other	2.1	

Metal Fraction - 3 Percent of Total Residue

Component	Weight Percent
Silicon	0.25-4
Copper	0.2-2.2
Carbon	< 1
Miscellaneous	< 1
Iron	balance

The process will produce approximately 770 kg (1700 lb) of wet gas (30 percent water), 90 kg (200 lb) of oil and tar, and 135 kg (300 lb) of slag from 0.9 metric ton (1 ton) of municipal solid waste and 0.18 metric ton (0.2 ton) of oxygen.(109)

The process has been operated on municipal and commercial refuse and is compatible with the full range of materials normally experienced in domestic and commercial refuse. A thermal efficiency of 75 percent can be obtained with municipal solid waste provided the refuse moisture content is less than 45 percent and the refuse heating value exceeds 1950 kcal/kg (3500 Btu/lb).(116)

Some of the advantages and disadvantages cited for the Purox Process are listed below.

Advantages

- Low nitrogen content of gas (minimal NO_x pollution)
- Relatively high heating value of gas. Application in existing power plant
- Large size demonstration project underway
- Ferrous metals are reclaimed

Disadvantages

- No reclamation of glass and aluminum
- Fuel gas not compatible with natural gas distribution network
- Storage of fuel not possible
- Requires high energy oxygen generating plant
- Energy consumption of oxygen generating facility, approximately 1/3 of gross reclaimed energy

Georgia Tech pyrolysis system--The Georgia Institute of Technology has developed a mobile, low temperature vertical shaft pyrolysis system. Most of the work has been done using agricultural or wood wastes, although limited testing has been done with municipal refuse. The primary objective of the process is to convert wet biomass waste into a low sulfur, char-oil fuel for use as a substitute for coal.

A flow schematic of the mobile process is presented in Figure 27.(117) The wet feed is continuously shredded and dried and introduced to the reactor, where at 400 to 500 C (750 to 930 F) the feed pyrolyzes to a wet gas and char. The use of low temperatures reduces the insulation requirements and mechanical and material design problems and favors the production of large amounts of char and small amounts of gas.

The wet gas exits the reactor and passes through a cyclone where particulates are removed and through a condenser where the liquid fraction is separated. Some of the gas is incinerated to provide the heat for drying the

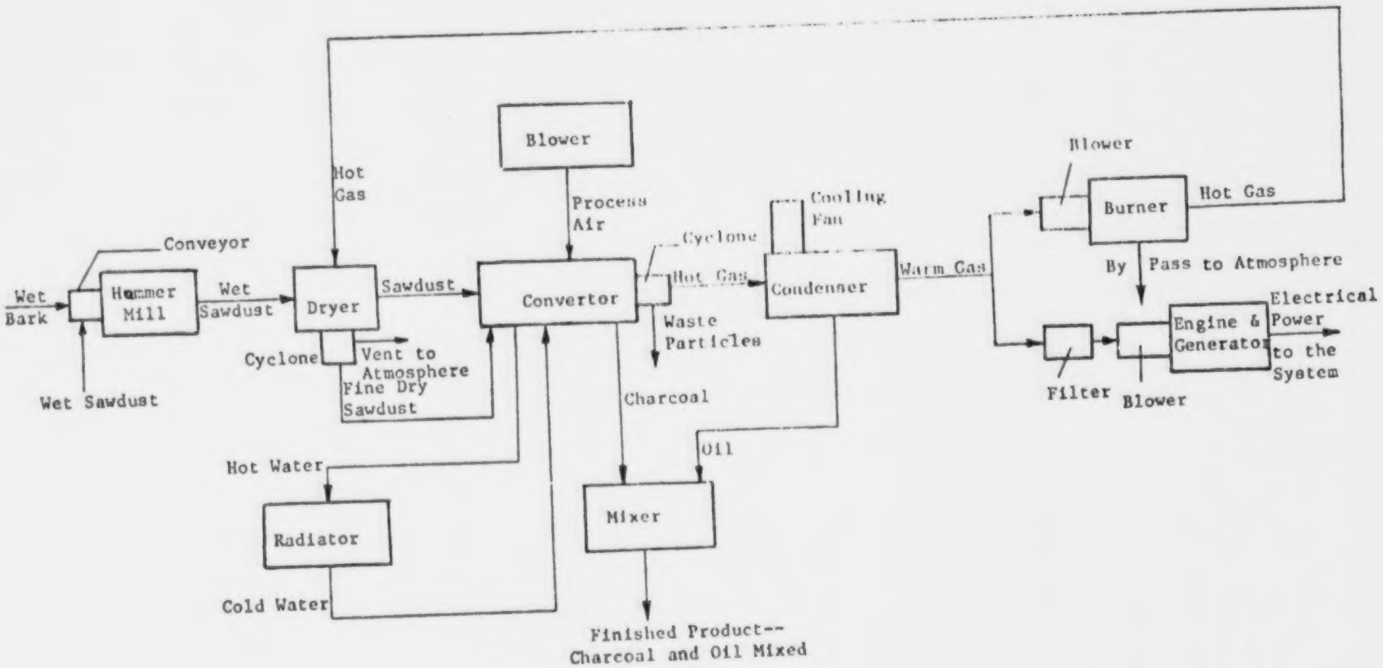

Wet Bark
Conveyor
Hammer Mill
Wet Sawdust
Wet Sawdust
Hot Gas
Dryer
Sawdust
Cyclone
Vent to Atmosphere
Fine Dry Sawdust
Blower
Process Air
Convertor
Cyclone
Hot Gas
Waste Particles
Charcoal
Cooling Fan
Condenser
Oil
Warm Gas
Hot Water
Radiator
Cold Water
Mixer
Finished Product--Charcoal and Oil Mixed
Blower
Burner
Hot Gas
By Pass to Atmosphere
Filter
Blower
Engine & Generator
Electrical Power to the System

Figure 27. Mobile pyrolysis unit process flow diagram.

feed, and the remainder is directed through a turbine electric generator to provide electrical power for the system. The char is withdrawn from the reactor and mixed with the condensed oil to form the product fuel.

When the feed contains little inert material, as in agricultural or wood wastes, the produced char has a high heating value [6100 - 7200 kcal/kg (11,000 - 13,000 Btu/lb)] and a low ash content. The use of municipal solid waste as a feed material, however, is expected to introduce more inert ingredients into the char and reduce its attractiveness as a fuel.(110)

No information was available on the thermal efficiency of the process.

Horizontal Shaft--

One horizontal shaft reactor process, the Barber-Colman Process, was examined in this study.

The Barber-Colman process--The Barber-Colman process utilizes indirect heating by the use of a molten lead heat transfer media in a horizontal shaft reactor. The process has been demonstrated on a 700 kg/day (1500 lb/day) pilot plant.

Figure 28 is a schematic flow diagram of the process.(110) The refuse is initially fed to a metal detector where the larger pieces of metal (15 cm or greater) are removed. The remaining material is shredded to about 5 cm (2 in.) and fed to the reactor via an air lock. In the reactor, the refuse floats on the molten lead surface where it is pyrolyzed at a temperature of about 650 C (1200 F) producing a gas with a heating value of 450 - 5400 kcal/m^3 (500 - 700 Btu/scf). The lead is circulated in the reactor via a gas lift pump operating on the produced pyrolysis gas and heated from the top by radiant tube burners. About one-fourth of the produced gas is consumed in the gas lift system; the remainder would be available for sale. The system has an overall efficiency of about 66 percent.

Some material dissolves and settles in the lead and at prescribed intervals a portion of the lead bath is withdrawn and reclaimed by the addition of new lead.

Rotary Kiln Reactors--

Two rotary kiln reactor processes, the Monsanto and Devco processes, were examined in this study.

Monsanto Landgard process--In the Monsanto Landgard process (Figure 29), mixed municipal solid waste is pyrolyzed with supplemental fuel in a horizontal reactor to form a solid residue and a low energy gas 1100 kcal/m^3 (120 Btu/scf).

Development of the system began in 1969 on a 0.27 metric ton per day (0.3 ton per day) pilot plant in Dayton, Ohio. The pilot plant was followed by a 32 metric ton per day (35 ton per day) prototype plant in St. Louis County, Missouri. Data from the prototypes were used to design a 910 metric tons per day (1000 tons per day) facility which began start-up in Baltimore, Maryland, in Spring of 1975.

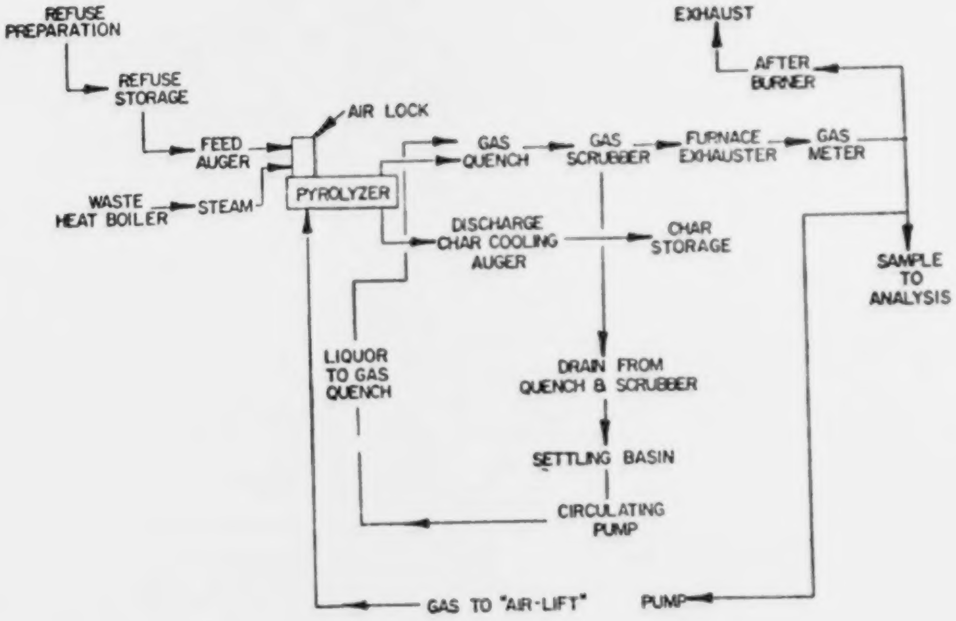

REFUSE PREPARATION
REFUSE STORAGE
FEED AUGER
AIR LOCK
WASTE HEAT BOILER
STEAM
PYROLYZER
GAS QUENCH
GAS SCRUBBER
FURNACE EXHAUSTER
GAS METER
EXHAUST
AFTER BURNER
DISCHARGE CHAR COOLING AUGER
CHAR STORAGE
SAMPLE TO ANALYSIS
LIQUOR TO GAS QUENCH
DRAIN FROM QUENCH & SCRUBBER
SETTLING BASIN
CIRCULATING PUMP
GAS TO "AIR-LIFT"
PUMP

Figure 28. Barber-Colman pyrolysis system flowsheet.(110)

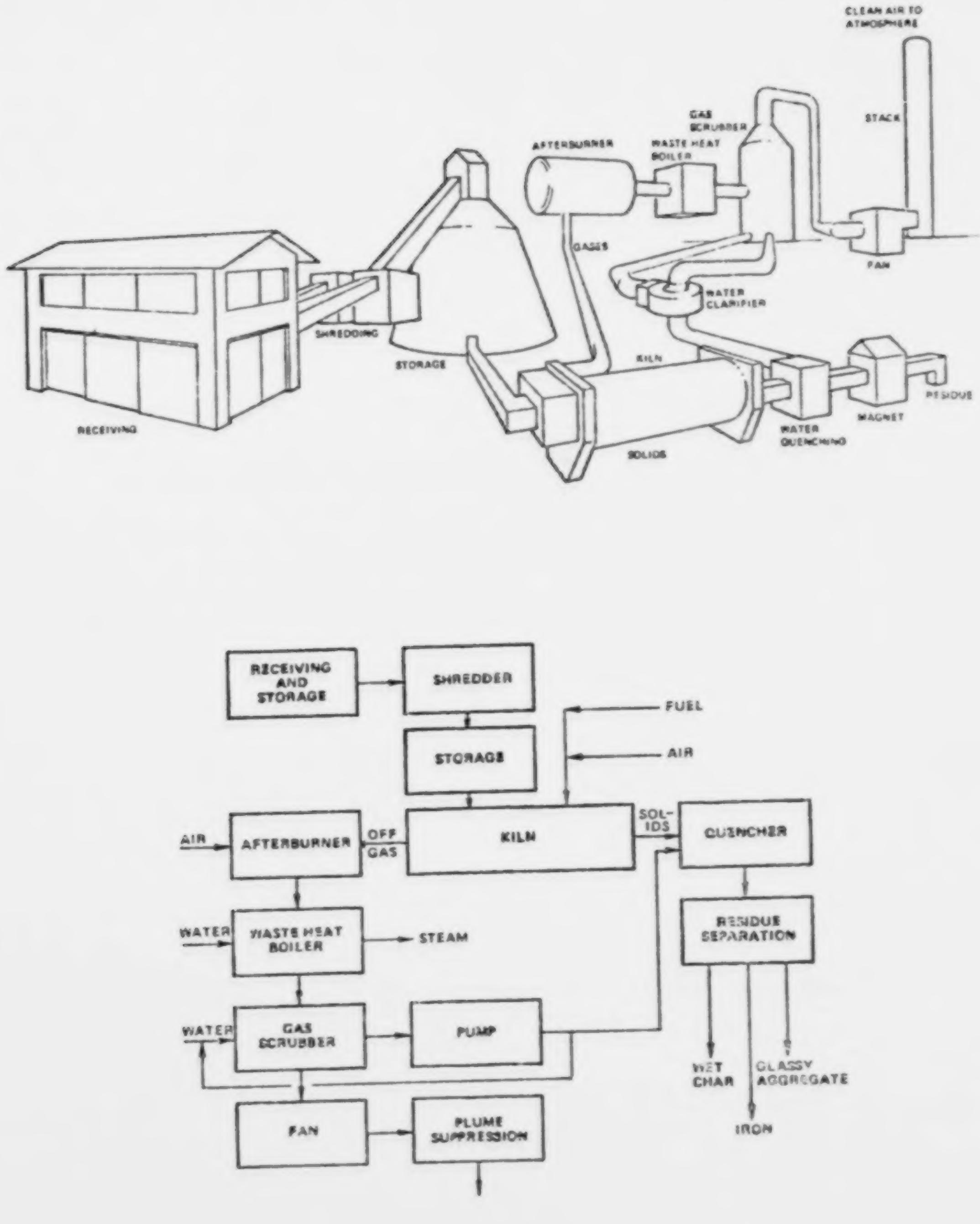

CLEAN AIR TO ATMOSPHERE
STACK
GAS SCRUBBER
AFTERBURNER
WASTE HEAT BOILER
GASES
FAN
WATER CLARIFIER
SHREDDING
STORAGE
KILN
RESIDUE
MAGNET
WATER QUENCHING
SOLIDS
RECEIVING
RECEIVING AND STORAGE
SHREDDER
STORAGE
FUEL
AIR
AIR
AFTERBURNER
OFF GAS
KILN
SOL-IDS
QUENCHER
WATER
WASTE HEAT BOILER
STEAM
RESIDUE SEPARATION
WATER
GAS SCRUBBER
PUMP
WET CHAR
GLASSY AGGREGATE
IRON
FAN
PLUME SUPPRESSION

Figure 29. Monsanto "Landgard" process.(119)

The Landgard process will accept any typical residential or commercial solid waste and sewage sludge; industrial wastes, however, are excluded. After removing oversize items, the waste stream is shredded into particles about 4 inches in diameter. The shredded refuse is fed by a hydraulic ram into the elevated end of a tilted, horizontal rotary kiln pyrolysis reactor. A portion of the solid waste is combusted using 40 percent of the air theoretically required for complete combustion. The remainder of the required heat is supplied by an oil burner, located at the discharge end of the kiln. The pyrolysis gases, formed by the heat of combustion, move countercurrent to the waste and exit the kiln at the feed end. The temperature of the burning refuse is maintained below 1100 C (2000 F) to prevent slagging of the residue; the temperature of the exit gas is approximately 650 C (1200 F). The produced pyrolysis gas is a low energy fuel with a heating value, based on MSW, of about 1100 kcal/m^3 (120 Btu/scf) and a composition typical of that shown below.(118)

Component	Percent by Volume, dry basis
Nitrogen	69.3
Carbon dioxide	11.4
Carbon monoxide	6.6
Hydrogen	6.6
Methane	2.8
Ethylene	1.7
Oxygen	1.6
	100.0

The pyrolytic gases, exiting the kiln, are directed into an afterburner (gas purifier) where they are combusted with additional air at about 760 C (1400 F). Modular waste heat boilers (heat exchangers) are utilized to recover approximately 91,000 Kg (200,000 lb) of steam per hour. After exiting the boilers, the gases are directed through a wet scrubber, a demister, and an induced draft fan, and vented to the stack.

The hot residue is discharged from the kiln into a water-filled quench tank and on to a flotation separator where the light carbon char is separated from the heavy material. The heavy material is further classified into ferrous metals and glass residue in a magnetic separator.

The residue carbon char consists of about 50 percent carbon (dry weight basis) with the remainder consisting of mostly glass and ash. An analysis of the char is presented in Table 51.

Approximately 72 metric tons per day (80 tons per day) of char residue, 64 metric tons per day (70 tons per day) of ferrous metal, and 154 metric tons per day (170 tons per day) of glassy aggregate are recovered from the 910 metric tons per day (1000 tons per day) pyrolysis facility when processing typical municipal solid waste.(118) At present, the char is disposed of in

TABLE 51. ANALYSIS OF CARBON CHAR RESIDUE(a)(118)

Component	
	Analysis, dry basis
Carbon	50.0%
Ash and glass	45.8%
Volatiles	4.0%
Sulfur	0.2%
	Analysis of water-extractable fraction
Sodium	over 30%
Calcium	0.1-1.0%
Copper	0.03-0.3%
Magnesium	0.03-0.3%
Potassium	0.03-0.3%
Boron	0.01-0.1%
Strontium	0.001-0.1%
Iron	0.001%*
Molybdenum	0.001%*
Silicon	0.001%*
Phosphorus	25 ppm*
Chromium	10 ppm*
Lead	10 ppm*
Tin	10 ppm*
Vanadium	5 ppm*
Zinc	5 ppm*
Aluminum	1 ppm*
Cadmium	1 ppm*
Manganese	1 ppm*
Silver	1 ppm*
Titanium	1 ppm*

(a) Bulk density, 325-811 kg per cubic meter
Moisture content, 50% by weight
Heating value, dry basis, 7,000 Btu per pound

*Less than figure shown.

a landfill, although it has been suggested that the char may have application as a soil conditioner when mixed with sewage sludge. The iron waste stream is reasonably free of contaminants (Table 52) and has been recommended for use in a melting stack for foundries. The glassy aggregate is relatively metal-free (Table 53) and is recommended for use in road construction in asphalt paving mixtures.(118)

The various advantages and disadvantages cited for the process are listed below.

Advantages

- 910 metric tons per day (1000 tons per day) commercial size plant has been built (though initial operations have been beset with difficulties)
- Reclaims glass and ferrous metals

Disadvantages

- Produces low-Btu gas fuel, primarily applicable for on-site generation of steam
- Storage of gas not possible
- Facility must be located in close proximity to steam consumer
- Requires supplemental fuel
- Disposal of solid residue is still a problem

Devco--Devco Management, Inc., has developed a rotary kiln pyrolysis process that is basically similar to the Monsanto Landgard process. The most notable differences in the Devco System are the lower kiln operating temperatures 540 C (1000 F) and the absence of shredding. Devco uses a proprietary "selective pulverizer" which breaks up the low tensile strength items in a low energy process.(110)

Tests have been conducted on a 6.4 metric tons per day (7 tons per day) pilot plant in Queens, New York, and a larger municipal solid waste pyrolysis unit, 136 metric tons per day (150 tons per day), is currently under construction in Brooklyn, New York.

As with the Monsanto process, the low Btu pyrolysis gas is combusted to produce saturated steam in a heat exchanger. The burned char product is claimed to have a heating value of 10,000 Btu/lb and produce less than 10 percent ash when burned.

Fluidized Bed Reactors--

The only fluidized bed pyrolysis process that has received significant attention in the literature is the West Virginia process.

West Virginia process--The West Virginia University fluidized bed reactor has been studied on an experimental scale on a 15-inch diameter vessel for the pyrolysis of municipal solid waste. Based on the results of the experiments, the process was revised and theoretically scaled up and evaluated as a 910

TABLE 52. QUALITY OF FERROUS METAL RECOVERED FROM PYROLYSIS RESIDUE (118) (a)

Component	Percent	Component	Percent
Iron	98.850	Antimony	.020*
Tin	.153	Sulfur	.016
Carbon	.150	Phosphorus	.015
Copper	.150	Cobalt	.010*
Nickel	.140	Molybdenum	.010*
Lead	.088	Titanium	.010*
Manganese	.048	Vanadium	.010*
Silicon	.045	Aluminum	.001*
Chromium	.035	Other	.249

(a) Bulk density, 576.5 kg per cubic meter
Iron, 98.85% by weight
Contaminants, 1.15% by weight

*Less than percent shown.

TABLE 53. ANALYSIS OF GLASSY AGGREGATE RECOVERED FROM PYROLYSIS RESIDUE (118)

Bulk density	2432 kg per cubic meter
Component	**Percent**
Glass	65
Rock and miscellaneous	28
Ferrous metal	3
Nonferrous metal	2
Carbon	2

metric tons per day (1000 tons per day) plant by the Stanford Research Institute. The process, as conceptually designed, produces a rich fuel gas by utilizing two fluidized beds and indirectly heating the solid wastes to avoid dilution of the fuel gas by air or oxygen.(119) A simple schematic is shown in Figure 30.

The solid waste is initially shredded, classified to remove noncombustibles, and dried prior to introduction into the gasifier. In the gasifier the shredded organic waste is contacted by hot sand at 815 C (1500 F) in a fluidized bed. The gases formed by the pyrolysis reaction in the oxygen-free atmosphere exit the gasifier and enter a cyclone separator where the entrained char is removed. The cleaned gas is relatively rich, with a heating value of about 3600 kcal/m^3 (400 Btu/scf); based on the pyrolysis of municipal waste the gas has the following composition.

Component	Percent by Volume (dry basis)
H_2	44.5
CO_2	15.8
CO	24.7
CH_4	7.0
C_2H_2	5.0
C_2H_4	1.5
C_2H_6	0.6
C_3H_8	0.9
	100.0

The sand withdrawn from the gasifier is fed to the combustor where it is heated to about 950 C (1750 F) by burning the char collected by the cyclone separator and the liquids recovered from the pyrolysis gas. The heated sand is then recycled to the gasifier to heat and pyrolyze the solid waste feed.

A side stream of sand and ash is removed from both the gasifier and combustor and screened to separate the sand from the waste ash.

The advantages and disadvantages for the process are cited below.

Advantages

- Pyrolysis gas is relatively rich and may be upgraded to natural gas pipeline quality

Disadvantages

- The two vessel process has not yet been experimentally proven on waste
- Pyrolysis gas fuel cannot be stored
- Process suffers from problems characteristic to fluidized bed reactors, i.e., entrainment and separation of particles

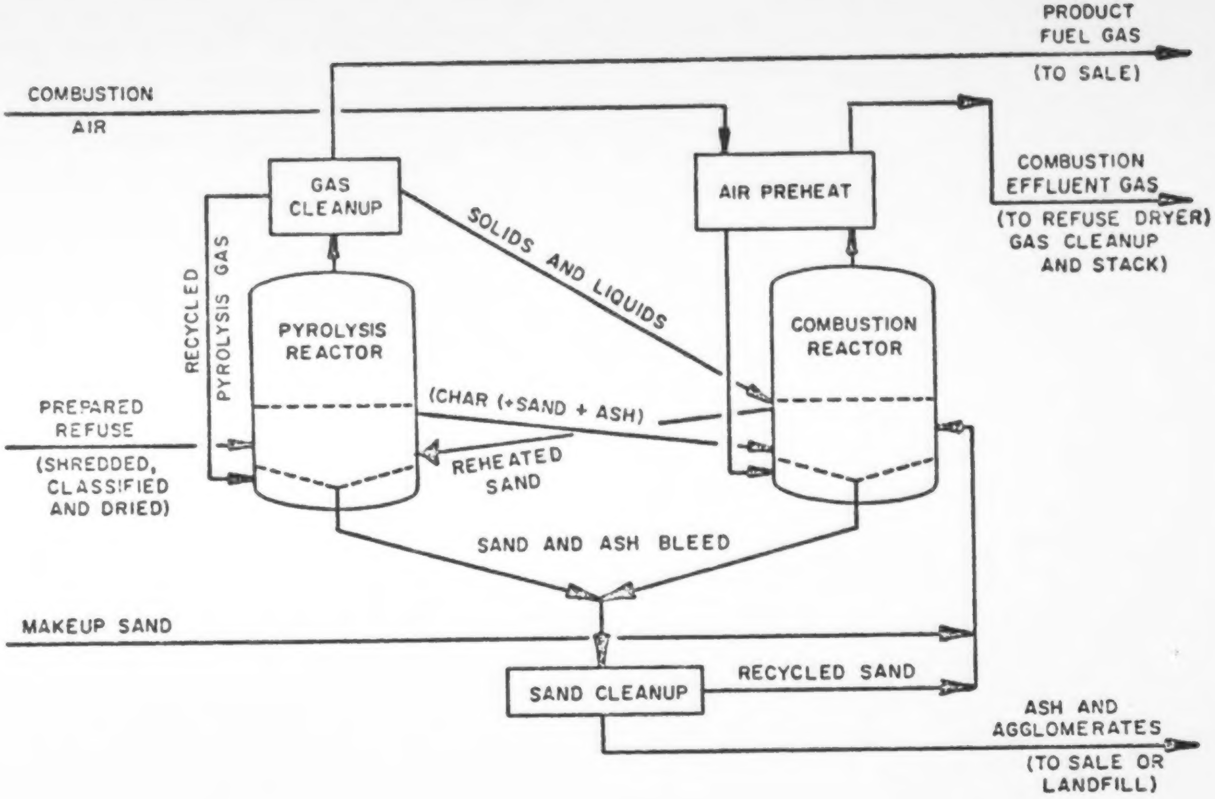

PRODUCT
FUEL GAS
(TO SALE)
COMBUSTION
AIR
GAS CLEANUP
AIR PREHEAT
COMBUSTION
EFFLUENT GAS
(TO REFUSE DRYER)
GAS CLEANUP
AND STACK)
RECYCLED
PYROLYSIS GAS
SOLIDS AND LIQUIDS
PYROLYSIS
REACTOR
COMBUSTION
REACTOR
PREPARED
REFUSE
(SHREDDED,
CLASSIFIED
AND DRIED)
(CHAR (+SAND + ASH)
REHEATED
SAND
SAND AND ASH BLEED
MAKEUP SAND
SAND CLEANUP
RECYCLED SAND
ASH AND
AGGLOMERATES
(TO SALE OR
LANDFILL)

Figure 30. Schematic of West Virginia University pyrolysis process.(119)

Other Applications of Pyrolysis for Biomass--

Additional small-scale (bench-scale or small pilot plant) research has been conducted on the pyrolysis of other wastes, livestock waste, municipal sewage, rubber tires, and automobile batteries to name a few. A description of some of the results of specific experiments is detailed below.

Cattle manure--Due to the relatively large volumes generated daily and the high organic content, the pyrolysis of cattle manure has received considerable attention. Several papers have been published on the pyrolysis of cattle manure and some experimental work (bench scale) was performed, primarily in the early 1970's. The results of two experimental research studies are presented herein; one study was conducted by the United States Bureau of Mines (USBM)(113); the other study was supported by the EPA.(120)

The Bureau of Mines study was performed in a small, closed batch reactor (Figure 31). The dried cattle manure was introduced to the reactor and pyrolyzed at 900 C (1650 F) to produce a gas, oil, and char product. An analysis of the yields and compositions of the products is shown in Table 54. The gas showed to be mainly a mixture of CO, CO_2, H_2, and CH_4. The light oil was predominantly aromatic, with about 87 percent benzene, toluene, and xylene. The char residue was about 50 percent ash and had a heating value of 4050 kcal/kg (7290 Btu/lb).

This study addressed the technological feasibility of pyrolyzing cattle manure; no recommendations or statements were made as to the commercial feasibility of such a process.

The EPA-funded study utilized a tubular reactor to pyrolyze the cattle manure. Helium scavanger gas was passed through the reactor to carry off the produced gases (Figure 32). Operating temperatures were at 400 to 500 C (750 to 930 F). The typical pyrolysis product yields and a gas analysis are shown in Tables 55 and 56.

Based on the results of the experiments, the process was scaled up and evaluated on an economic basis. The evaluation concluded that, with predrying the manure, the low energy recovery efficiency (20-30 percent) does not make the process competitive with simple incineration when used to produce energy fuels. The process was also plagued by environmental liabilities. The light oils had a pestiferous odor and there was fear that the manure pyrolysates would be carcinogenic, although no studies were conducted to substantiate this belief.

Rubber tires--In 1969, the Firestone Rubber and Tire Company and the USBM investigated the feasibility of applying the pyrolysis technique to used automobile tires in the USBM 3.5 cubic foot batch reactor; a process flow schematic is presented in Figure 31, the same as used for manure.

Experiments were conducted at temperatures ranging from 140 C to 900 C with residence times of 7 to 14 hours.(121) The experiments at low temperatures resulted in high yields of oil and small quantities of gas. The inverse was true for the high temperature experiments. Typical yields of the pyrolysis products are shown as follows.(121)

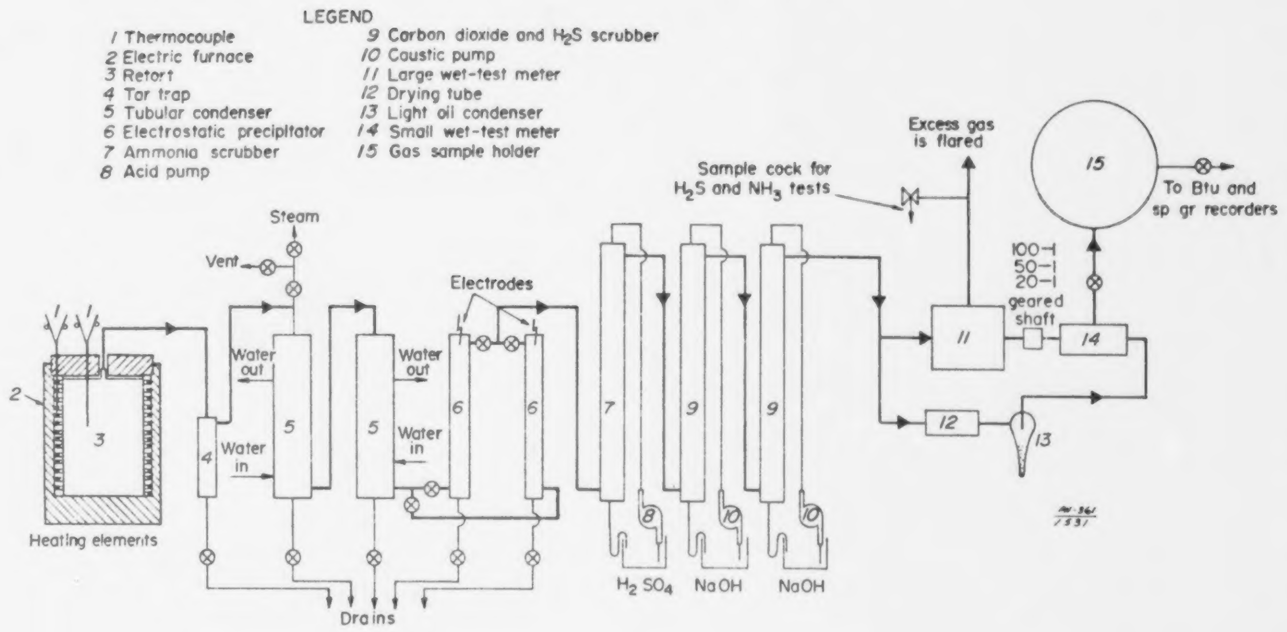

LEGEND
1 Thermocouple
2 Electric furnace
3 Retort
4 Tar trap
5 Tubular condenser
6 Electrostatic precipitator
7 Ammonia scrubber
8 Acid pump
9 Carbon dioxide and H2S scrubber
10 Caustic pump
11 Large wet-test meter
12 Drying tube
13 Light oil condenser
14 Small wet-test meter
15 Gas sample holder
Steam
Vent
Water out
Water in
Electrodes
Heating elements
Drains
H2SO4
NaOH
NaOH
Sample cock for H2S and NH3 tests
Excess gas is flared
100-1
50-1
20-1
geared shaft
To Btu and sp gr recorders

Figure 31. Bureau of Mines experimental pyrolysis apparatus.(113)

TABLE 54. BOVINE WASTE PYROLYZED AT 900 C(113)

Ultimate analysis of feed wt percent*		
C	41.2	
H	5.7	
O	33.3	
N	2.3	
S	0.3	
Ash	17.2	
Yields	Wt percent of feed	Per .9 MT (1 ton) of feed
Gas	38.5	390m^3 (13,940 cu ft)
Oil	5.8	49 liters (13.0 gal)
Aqueous	15.9	143 liters (38.3 gal)
$(NH_4)_2SO_4$	0.15 (NH_3)	30 kg (65.8 lb)
Residue	36.3	330 kg (726 lb)
Gas composition. vol percent		
CO_2	24.5	
CO	18.0	
H_2	27.5	
CH_4	22.7	
C_2^+	7.3	
Analysis of residue, wt percent		
C	49.4	
H	0.4	
O	0.4	
N	1.1	
S	0.3	
Ash	48.4	
Heating values		
Feed, kcal/kg (Btu/lb)	3950 (7,110)	
Gas, kcal/m^3 (Btu/scf)	4050 (450)	
Residue, kcal/kg (Btu/lb)	4050 (7,290)	

* Dried to 3.6 percent moisture.

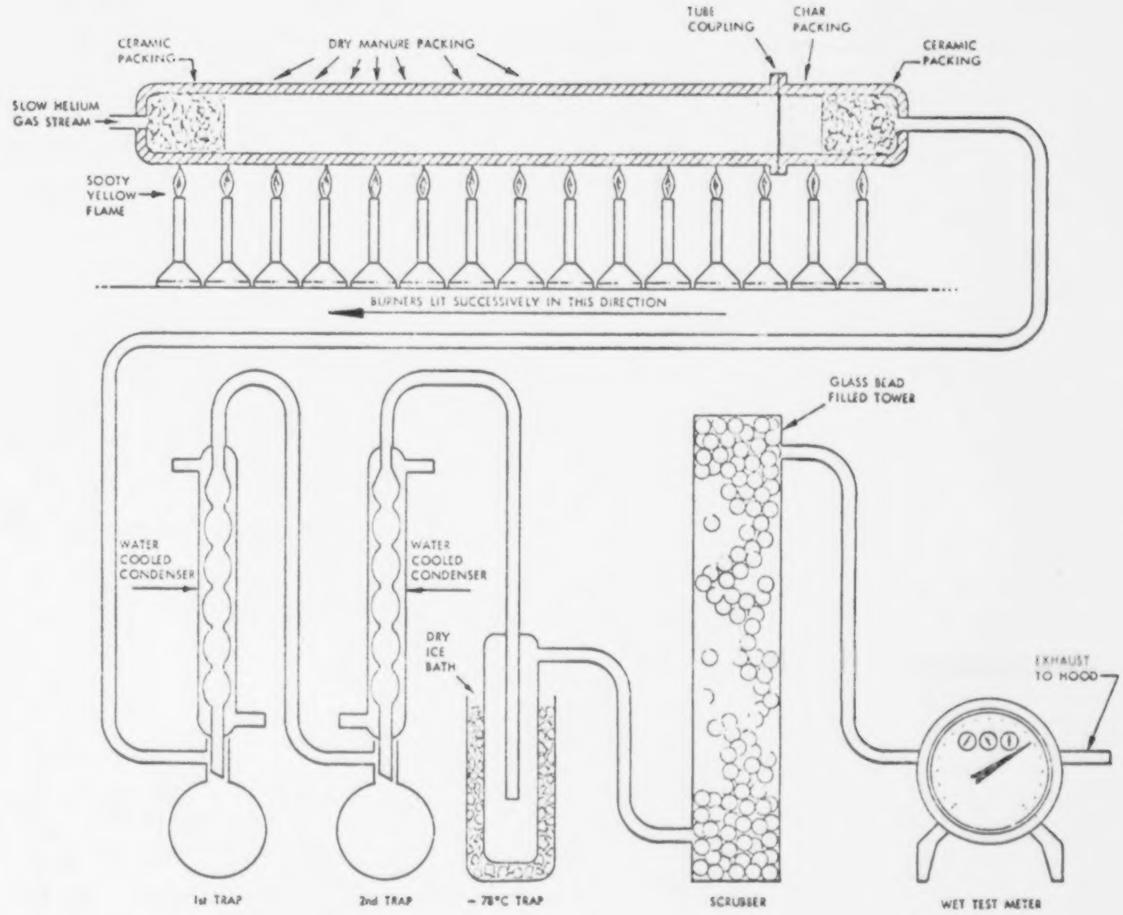

CERAMIC PACKING
DRY MANURE PACKING
TUBE COUPLING
CHAR PACKING
CERAMIC PACKING
SLOW HELIUM GAS STREAM
SOOTY YELLOW FLAME
BURNERS LIT SUCCESSIVELY IN THIS DIRECTION
GLASS BEAD FILLED TOWER
WATER COOLED CONDENSER
WATER COOLED CONDENSER
DRY ICE BATH
EXHAUST TO HOOD
1st TRAP
2nd TRAP
− 78°C TRAP
SCRUBBER
WET TEST METER

Figure 32. Experimental pyrolysis apparatus.(120)

TABLE 55. TYPICAL YIELDS OF PRODUCTS FROM THE PYROLYSIS OF CATTLE MANURE(120)

Compound	Wt percent[a]
Water	24
Volatile	1
Tar	2
Noncondensible	32
Char	41
	100

(a) Raw feed dried to 7 percent moisture.

TABLE 56. TYPICAL COMPOSITION OF PRODUCT GAS FROM THE PYROLYSIS OF CATTLE MANURE(120)

Compound	Mole percent (dry basis)
H_2	8.6
N_2	10.9
O_2	-
CO	16
CO_2	38.9
CH_4	12.9
C_2H_4	0.3
C_2H_6	1.8

Temperature C	Residue	Light Oil	Heavy Oil	Gas	Total
500	42.0	4.2	45.2	5.0	96.7
900	52.3	6.5	14.5	20.8	97.3

Based on these data, it was estimated that 0.9 metric ton (1 ton) of pyrolyzed tires would produce the following.

Gas - 320 m^3 (11,460 ft^3)
Oil - 194 liters (51.5 gallons)
Residue - 474 kg (1,046 lb)

The product gas contained over 50 percent hydrogen and had a heating value of 6300 kcal/m^3 (700 Btu/scf). The residue contained mostly carbon with about 10 percent ash and had a heating value of 7500 kcal/kg (13,500 Btu/lb).

Raw sewage--The USBM(113) also conducted pyrolysis experiments using sewage sludge as feed. The raw sewage sludge was initially dried to 23.5 percent moisture and pyrolyzed at 500 to 900 C. The yields and some of the product analyses are shown in Table 57.

Environmental Aspects--

The two most significant environmental impacts of the pyrolysis systems are (1) the reduction in landfill or disposal requirements of the wastes, particularly municipal waste; and (2) the reduction in fossil fuel requirements corresponding to the energy content of the produced fuel. Pyrolysis is also regarded as being more environmentally appealing than incineration as a method for waste-to-energy conversion due to the lower air requirements and reduced total volumes of flue gas (and associated pollutants) per ton of fuel.

There is very little "hard" information available on the integrity of the effluent streams from pyrolysis processes. And there is similarly limited information on whether or not pyrolysis does present a significantly lower environmental impact than does incineration. Table 58 presents a calculated comparison of emissions from various thermal processes.(112) It was stated that the results in Columns 1 and 2 are not strictly comparable, as different waste streams were used and could have varied widely in composition. The significant aspect is the lower SO_2 and NO_x emissions generated from thermal processing of municipal waste as opposed to burning coal or fuel oil.

A prediction of the quality of the effluents from the Monsanto Landgard facility in Baltimore, Maryland, generally concurs with the data in Table 58.(118) The particulates were expected to be less than 0.03 grains per cubic foot, and the SO_2 and NO_x emissions will be less than 100 ppm and 50 ppm, respectively.

Hydrolysis - Acid-Based

Cellulosic bearing materials can be hydrolyzed in the presence of an acid to form glucose.

TABLE 57. PYROLYSIS OF RAW SEWAGE(113) (500-900 C)

Yields per 0.9 metric ton (1 ton) fuel:	
Gas, m^3 (scf)	254 (9100)
Light oil, liters (gallons)	21 (5.6)
Tar, liters (gallons)	87 (23.2)
Ammonium sulfate, kg (lb)	18 (40.2)
Aqueons , liters (gallons)	242 (64.1)
Residue, kg (lb)	262 (576)
Heating value of gas, kcal/m^3 (Btu/scf)	6615 (735)

TABLE 58. STACK GAS ANALYSES, PPM BY VOLUME CORRECTED TO 12 PERCENT CO_2(112)

	Municipal Waste		Other Fuels		
	Pyrolysis	Incineration	Natural Gas	No. 6 Fuel Oil	Coal
Sulfur dioxide	130	100	0.3	500	3,500
Nitrogen oxides	55	80	170	450	360
Hydrocarbons	9	17	-	6	12
Chloride	20	440	-	-	-
Particulates, gr/scf	0.03	0.04	0.01	0.02	1

$$C_6H_{10}O_5 + H_2O \rightarrow C_6H_{12}O_6$$

The generated glucose may then be used for a variety of purposes, one of which is a feedstock for the fermentation to ethyl alcohol.

$$C_6H_{12}O_6 \xrightarrow{\text{Yeast}} 2C_2H_5OH + 2CO_2$$

Although cellulosic materials such as corncobs, cottonseed hulls, peanut shells, and bagasse have been proposed as potential feedstock for the hydrolysis-fermentation sequence, only wood pulp and wood waste feeds have been proven on a commercial scale. The waste disposal problem and the energy crisis have engendered interest in utilizing municipal waste as a feedstock; however, the scope of work has been limited to bench-scale experimentation and evaluation.

Two fundamentally different acid-based processes have been utilized for the production of sugar from wood: (1) dissolving the cellulosic material in a concentrated-acid, followed by dilution and distillation, and (2) hydrolysis in a dilute-acid solution at elevated temperatures and pressures followed by separation of the acid and sugar.

The concentrated-acid process was applied on a commercial basis on a 300 metric ton per day plant in Regensburg, Germany, during World War II. The process, referred to as the Bergins process, was based on an earlier patent by Willstathter.(122) Chipped wood feed was dissolved in a 42-45 percent solution of HCl, followed by washing to remove the acid from the residue and distillation to recover the acid. The remaining hydrolyzate was spray-dried and used in the production of yeast fodder. The concentrated-acid process produced a comparatively pure sugar product but required large quantities of highly-corrosive reagent acid.

The dilute-acid process received its first industrial trial at the beginning of this century. The process was first applied in a plant at Georgetown, South Carolina, then at one in Fullertown, Louisiana. These plants manufactured about 19,000 to 26,000 liters (5,000 to 7,000 gallons) per day of alcohol from sawdust. Single-staged batch reactors were used in which the sawdust feeds was hydrolyzed in the presence of a dilute sulfuric acid catalyst. The low-yields, approximately 7 liters of 100 percent alcohol per 100 kg of southern pine sawdust (20 gal/ton), and a decrease in the price of blackstrap molasses resulted in the closing of both plants within 2 years after World War II.(123)

The major drawback to the single-stage batch process is that the rate of sugar production and destruction are almost equal. As a result, the yields from the batch-wise process as practiced are only about one-third of the theoretical yield. To improve the efficiency of the dilute-acid process, Scholler developed a process in which dilute acid is injected into the top of the hydrolysis vessel and withdrawn through a screen in the bottom. In this manner, sugar production and extraction proceed simultaneously with the sugar being withdrawn and immediately cooled to stop the destruction reaction. The hydrolysis-extraction operation was accomplished by alternately percolating

0.6 percent sulfuric acid through the wood feed and injecting steam into the top of the reactor to press the solution out the bottom. This process produced a 3 percent sugar solution with a 60 to 70 percent recovery efficiency. Typical yields were 21 liters per 100 kg of wood (61 gallons per ton). The process was applied on a commercial scale in Germany and Switzerland during World War II; the plants are no longer operative.

In 1943, the War Production Board recommended a study of the Scholler process by the U.S. Forest Products Laboratory. A pilot-plant facility was constructed based on a modification of the Scholler process, and the Vulcan Copper and Supply Company was requested to operate the plant and conduct the design of a commercial scale plant. The commercial plant was subsequently constructed in Springfield, Oregon, in 1944 with a design throughput of 201 metric tons per day (221 TPD) of sawmill waste for a production of 41,600 liters (11,000 gallons) of 190 proof alcohol.(122) The actual production rate, however, fell far short of the design rate and in total approximately 189,000 liters (50,000 gallons) of ethyl alcohol were produced before the plant was surrendered to the Reconstruction Finance Corporation in 1947.

The pilot-plant operations begun at Marquette, Michigan, were transfered to Madison, Wisconsin, where a process referred to as the Madison Wood-Sugar Process was developed. This process involved percolating dilute sulfuric acid through a reactor charged with wood. The process required shorter residence times than the Scholler process (2.5 hours as opposed to 16 hours), less heat input, and higher alcohol yields.(122) In the process, chipped wood waste (chips, sawdust, and slabs) with up to 25 percent bark was loaded into large reactors (Figure 33). Steam was passed through the bed of chips to heat them to approximately 150 C. Dilute acid, with an initial concentration of approximately 2 percent was introduced into the reactor until the average acid concentration reached 0.6 percent at which time the feed acid concentration was decreased to 0.6 percent. After a short initial holding period (20 minutes), continuous injection of the dilute acid and withdrawal of the sugar product was begun during which the temperature of the inlet acid stream was increased to 185 C. The run was continued at the 185 C temperature for about 2 hours. At the end of the percolation, after draining the charge, the liquor was emptied from the reactor.

The sugar solution removed from the bottom of the reactor was flashed from 20 atm pressure to cool it to 30 C and stop the associated destructive reactions.(124) The solution was neutralized with lime and filtered to produce a filtrate containing 5 percent reducing sugar which was concentrated to a 50 percent molasses product; sugar yields ranged from 45 to 55 percent. Approximately 58 kg (130 lb) of sulfuric acid and 45 kg (100 lb) of lime were required per 0.9 metric ton (ton) of hydrolyzed bark-free wood waste.(124)

Additional tests were run on the pilot plant to evaluate the feasibility of a hydrolysis-fermentation operation. Some of the results, showing the volumes of reducing sugar and produced alcohol per metric ton of wood feed are given in Table 59.(125) Other by-products of the hydrolysis reaction were (1) liquor, constituting the bulk of the insoluble residue, (2) methanol, discharged with the flash stream from the hydrolyzer, (3) acetic acid, in solution with the hydrolyzate and in steam from the hydrolyzer, (4) furfural,

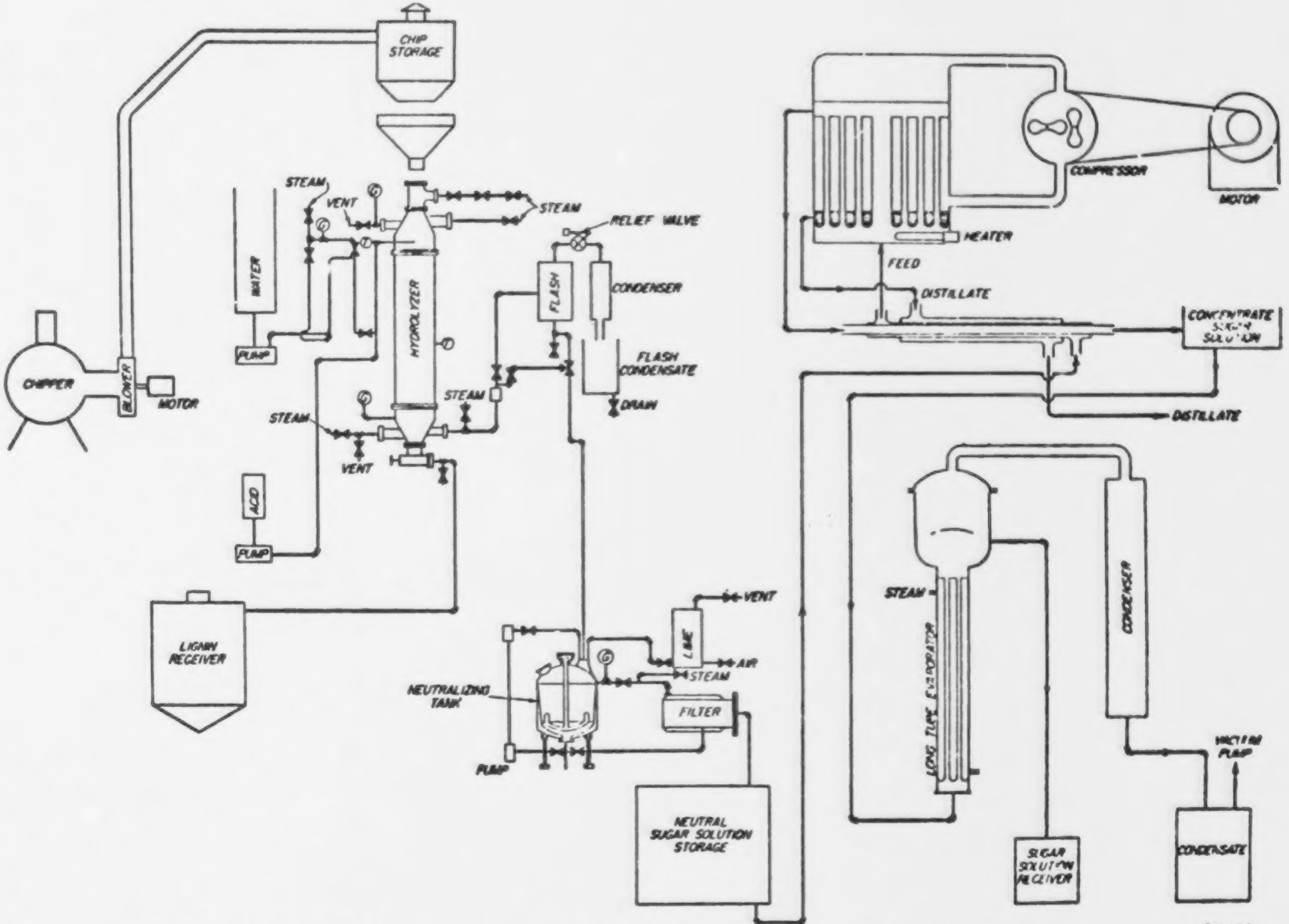

CHIP STORAGE
CHIPPER
BLOWER
MOTOR
WATER
PUMP
ACID
PUMP
STEAM
VENT
STEAM
VENT
STEAM
HYDROLYZER
STEAM
STEAM
RELIEF VALVE
FLASH
CONDENSER
FLASH CONDENSATE
DRAIN
LIGNIN RECEIVER
NEUTRALIZING TANK
PUMP
LIME
VENT
AIR
STEAM
FILTER
NEUTRAL SUGAR SOLUTION STORAGE
COMPRESSOR
MOTOR
HEATER
FEED
DISTILLATE
CONCENTRATE SUGAR SOLUTION
DISTILLATE
STEAM
LONG TUBE EVAPORATOR
CONDENSER
SUGAR SOLUTION RECEIVER
VACUUM PUMP
CONDENSATE

Figure 33. Flow chart for forest products laboratory process for producing molasses from wood.(124)

TABLE 59. TYPICAL HYDROLYSIS YIELDS(125)

Type of Wood	Wt. of Dry Wood (kg)	Total Wt. of Sugar Solution (kg)	Reducing Sugar Concentration (%)	Yield of 95% Alcohol (liter/metric ton)
Spruce Chips	147	1,434	5.3	210
Douglas Fir Chips	178	1,693	5.0	227
Pine Chips	159	1,480	5.0	210
Fir Chips	193	2,000	5.5	219
Redwood Chips	163	1,704	4.0	168
Turpentine Spent Chips	230	1,760	4.2	151
Oak Saw Dust	246	2,154	5.0	147
Maple Slabs	186	2,000	4.7	151

TABLE 60. ADDITIONAL HYDROLYSIS BY-PRODUCTS (124,126)

Item	Quality (wt. percent per metric ton of dry wood waste feed)
Lignin	25-30
Methanol	0.5-1.5
Acetic Acid	1.5-5.0
Furfural	0.1-1.0
Nonfermentable Sugars	5.0

resulting from the decomposition during hydrolysis and discharged with the flash steam, (5) nonfermentable sugars in the hydrolyzate solution, and (6) uronic acid and other sugar decomposition products. The representative quantities of most of these by-products are given in Table 60.(124,126) The Madison Pilot-Plant produced several hundred tons of wood-sugar and a larger plant, based on an adaptation of the process, was operated by the Tennessee Valley Authority for a short time following World War II.(127)

None of the above processes survived the post-World War II era. The world demand for yeasts was easily met by cane and beet molasses, sulfite liquor, whey and fruit products,(127) and the cost for generating ethanol could not compete with ethanol derived from petroleum feedstock. As mentioned, however, the recent increase in the cost of petroleum-based chemicals and the waste disposal problem have rekindled interest in acid hydrolysis of cellulosic bearing wastes (wood waste, refuse, etc.) as an economically feasible method for the production of reducing sugars for subsequent fermentation to ethanol. Current research has been limited to laboratory bench-scale studies, some of which have been conducted at Dartmouth College. Hydrolysis decomposition rate data were utilized in the design of a mini-size reactor for hydrolyzing municipal refuse to sugar. A 1/4-inch diameter continuous plug flow reactor was used to model the hydrolysis yields as a function of the temperature and residence times. Sugar yields from refuse reached 53 percent with residence times of 20 seconds and operating temperatures of 230 C. The feed slurry was, however, very dilute (1 percent) and resulted in low glucose product concentrations (0.3 to 0.5 percent). Based on these results a full scale plant processing 225 metric tons per day (250 TPD) of municipal refuse was conceptualized.(128)

The conceptual process involves pretreatment by the Black Clawson "Hydrosposal" process followed by hydrolysis in a tubular flow reactor with recycle, a neutralizer, and an evaporator to concentrate the sugar product (Figure 34).

Hydrogenation

Hydrogenation of biomass, or other organic bearing materials, involves reacting hydrogen (generally contained in a synthesis gas) with the organic substance under elevated temperatures and pressures. The produced synthetic gaseous or liquid fuel generally has a higher heating value than fuels customarily obtainable via other processes, e.g., pyrolysis.

The use of hydrogenation has been more extensively evaluated for the production of synthetic gases from coal and as yet has found only limited application for biomass waste. Two processes that have been demonstrated in part, for converting biomass waste into synthetic fuels, are the Battelle hydrogasification process and the Pittsburgh Energy Research Center's (formerly U.S. Bureau of Mines) COSTEAM process.

Battelle Hydrogasification Process--

Battelle's Columbus Laboratories have recently developed a process utilizing a hydrogasifier to convert solid waste into a rich synthesis gas amenable to upgrading to pipeline quality. The hydrogasification unit has been demonstrated on a 0.14 metric ton per day pilot plant (0.15 TPD), and an 1800 metric ton per day (2000 TPD) large-scale facility has been conceptualized for processing municipal solid waste.

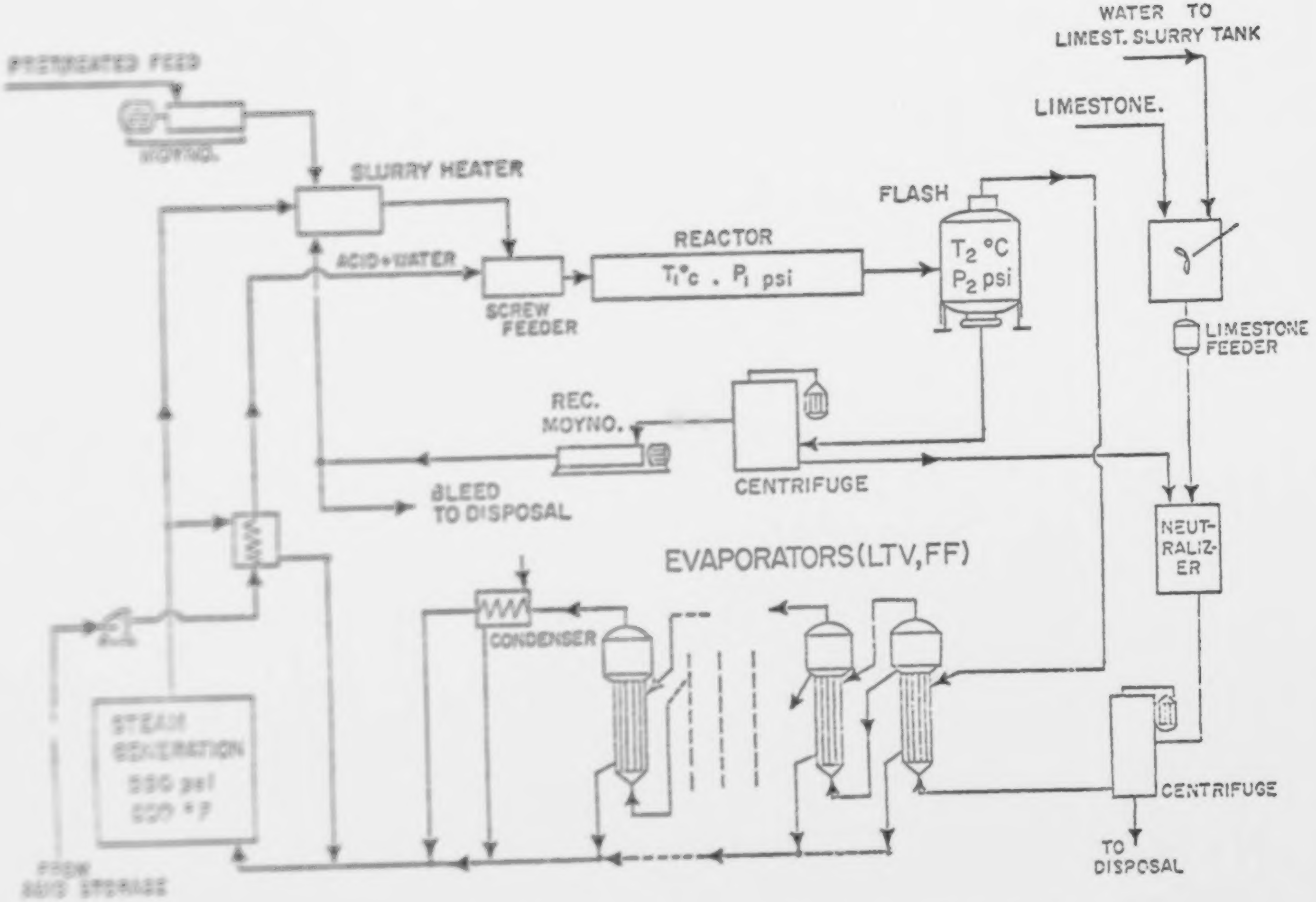

WATER TO
LIMEST. SLURRY TANK
PRETREATED FEED
MOYNO.
LIMESTONE.
SLURRY HEATER
FLASH
T_2 °C
P_2 psi
REACTOR
T_1°c . P_1 psi
ACID+WATER
SCREW FEEDER
LIMESTONE FEEDER
REC. MOYNO.
CENTRIFUGE
BLEED
TO DISPOSAL
NEUT-RALIZ-ER
EVAPORATORS(LTV,FF)
CONDENSER
STEAM GENERATION
FROM
CENTRIFUGE
TO DISPOSAL

Figure 34. Conceptual acid hydrolysis plant based on municipal solid waste.

A schematic flow diagram of the conceptualized process is shown in Figure 35. The shredded (unseparated) municipal waste is fed from the feed hopper through the pressurized lock hoppers (17 atm.) and into the top of the hydrogasification reactor. The waste fuel is charged to a free-fall or moving-bed reactor where it countercurrently contacts 1100 C (2000 F) synthesis gas stream composed predominantly of hydrogen. The synthesis gas heats the waste to approximately 550 C (1000 F), converting it to a medium grade [about 4500 kcal/cubic meter (400 Btu/cubic foot)] syngas which exits the top of the reactor.

The unreacted solids pass through the bottom of the reactor into a stripping zone where injected steam entrains the organic char, separating it from the heavier inert (metal and glass) portion. The inert solids are quenched to generate supplemental steam and processed to recover ferrous metals and glass. The separated char is transported to the oxygen-fed water-gas shift reactor where it is combusted and converted into the hydrogen-rich synthesis gas. Any ash residue is withdrawn from the bottom of the gasifier and disposed of by any appropriate means.

Tests were conducted in the hydrogasifier in both the free-fall and moving-bed mode using a mixture of 25 weight percent raw potatoes and 75 weight percent paper. Typical results and operating conditions from a run made on the moving-bed are given in Table 61. Typical results made with the solid waste in free-fall are given in Table 62. These tests were conducted with a pure hydrogen feed gas rather than a synthesis gas, and heat was supplied indirectly through the reactor wall. Major advantages cited for the process are as follows.

(1) It permits the use of unseparated waste feed and postpones the separation and recovery of inert materials until after the hydrogasification step. This concept is believed to enable easier separation of the organic from the inert material due to the increased density differences.

(2) It produces a raw product gas amenable to purification and methanation by existing technology.

The major disadvantages are the more complicated and interdependent reactor systems and the early stage of development. The system should be easily amenable to processing other biomass feedstocks.

COSTEAM--

DOE's Pittsburgh Energy Research Center (formerly U.S. Bureau of Mines) developed a process for converting solid organic wastes (paper, wood, manure, etc.) into a useful fuel oil by heating the solid to about 300 C under carbon monoxide and steam pressure (100-300 atm) and in the presence of a sodium carbonate catalyst, water and recycle oil.(129) Bench-scale tests were conducted in a 500-ml autoclave, and limited continuous flow experiments were performed on a 0.45 kg/hr reactor using a variety of waste feeds. Based on the results, a 2.7 metric ton per day pilot plant was designed to process carbonaceous wastes. The plant, currently in operation in Albany, Oregon, under DOE sponsorship, is designed to convert waste wood into liquid fuel.

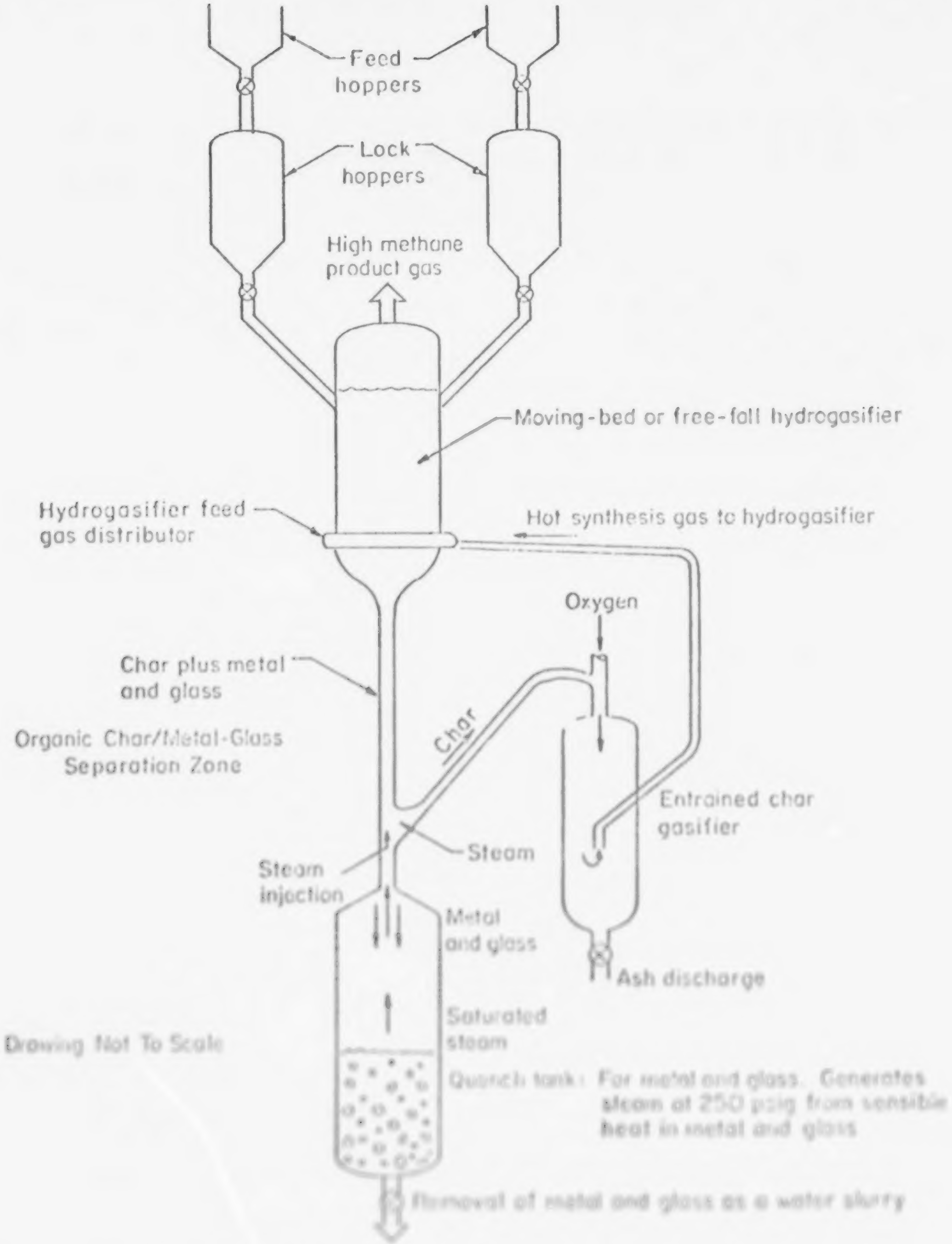

Feed hoppers
Lock hoppers
High methane product gas
Moving-bed or free-fall hydrogasifier
Hydrogasifier feed gas distributor
Hot synthesis gas to hydrogasifier
Oxygen
Char plus metal and glass
Organic Char/Metal-Glass Separation Zone
Char
Entrained char gasifier
Steam
Steam injection
Metal and glass
Ash discharge
Saturated steam
Drawing Not To Scale
Quench tank: For metal and glass. Generates steam at 250 psig from sensible heat in metal and glass
Removal of metal and glass as a water slurry

Figure 35. Conceptual solid waste gasifier system.

TABLE 61. TYPICAL EXPERIMENTAL RESULTS OF HYDROGASIFICATION OF SOLID WASTE IN A MOVING BED REACTOR

Solid Waste Feed Rate = 3.95 kg (8.69 lb) (dry basis)
4.72 kg (10.4 lb) (as fed basis)
per hour

Hydrogen Feed Rate = 2.8 cu m, 100 scf, per hour

Pressure = 18 atm

Temperature = 840 C (1550 F)

Approximate Solid Waste Residence Time = 21 minutes

Carbonaceous Char Yield = 0.154 kg/kg waste as fed

Oil Yield = 0.008 kg/kg waste as fed

Water Yield = 0.400 kg/kg waste (dry basis)

Product Gas Yield = 0.86 cu m/kg dry waste
(14.0 std cu ft/lb dry waste)

Product Gas Composition
(volume percent, dry basis)

H_2 = 32.42

CH_4 = 27.34

CO = 24.20

CO_2 = 13.30

C_2H_6 = 1.50

C_6H_6 = 0.50

N_2 = 0.74

100.00

TABLE 62. TYPICAL EXPERIMENTAL RESULTS OF HYDROGASIFICATION OF SOLID WASTE IN A FREE-FALL REACTOR

Solid Waste Feed Rate = 6.2 kg (13.5 lb) as fed, 4.8 kg (10.5 lb) as dry, per hour

Hydrogen Feed Rate = 2.8 cu m, 98 scf per hour

Pressure = (18 atm)

Reactor Temperature = 870 C (1600 F)

Approximate Solid Waste Residence Time = 1 second

Carbonaceous Char Yield = 0.271 kg/kg waste as fed

Oil Yield = not measured (less than 1%)

Water Yield = 0.247 kg/kg of dry waste

Product Gas Yield = 1.05 cu m/kg dry waste (16.3 std cu ft/lb dry waste)

Product Gas Composition
(volume percent, dry basis)

H_2 = 61.1
CH_4 = 12.9
CO = 17.4
CO_2 = 4.6
C_2H_6 = 1.5
C_2H_4 = 0.1
C_6H_6 = 0.6
N_2 = 1.8
100.0

A process flow schematic of the plant is provided in Figure 36. The waste wood chips will be initially dried and shredded to a -50 mesh particle size and slurried with the recycle product oil. A catalyst solution, consisting of sodium carbonate in water, will be blended with the wood-oil feed slurry. The resulting mixture will be preheated to about 230 C and introduced into one of two lock hoppers, operating in alternate sequence, where the mixture will be pressurized to 100 to 275 atm with carbon monoxide. The slurry will be fed continuously to the reactor, where at 230-400 C and under steam pressure, it will contact a gaseous mixture of CO and H_2. The liquid product will flow from the bottom of the reactor where it will be cooled and depressurized. An oil centrifuge will separate the oil from the water. The water will be collected in a sludge drum for disposal, and the oil will be filtered and pumped to the recycle storage tank from where it will be withdrawn either as product or recycle oil. Gases from the reactor bottoms flash tank will be cooled to condense the heavier ends and flared. The reactor off-gases will also be cooled to capture any condensate and flared. Condensate from both gas streams will be disposed of and any char collected in the bottom of the reactor will be withdrawn and disposed.

The oil yields are sensitive to operating pressures, temperatures, reactor residence times, and feed type and are not clearly defined. Bench-scale studies indicate, however, that oil yields can exceed 30-40 weight percent of the raw wood feed. The oil product is highly oxygenated, containing in excess of 4 percent oxygen, has a viscosity in excess of 50 centistokes, and, depending on the oxygen content, will have a heating value in the range of 5600 to 9400 kcal/kg (10,000 to 17,000 Btu/lb).(130,131) The oil is reportedly very low in sulfur.(129)

The condensates from the reactor off-gas, reactor product flash tank, wood chip dryer and preheater, and the process water from the centrifuge constitute the liquid waste streams. Little is known about the environmental integrity of these streams, and they may require treatment prior to discharging into the municipal sewage system.

The gaseous waste streams are all flared and are not expected to present a pollution problem. This conclusion should be substantiated, however, by monitoring the composition of the gas streams.

Naval Stores Industry

The naval stores industry involves the production of turpentine, rosin, pine oils, rosin oils, pine-pitches and tars from coniferous trees, specifically southern long leaf and slash pine. The industry dates back to the early 1600's when the products were used principally in the manufacture of wooden ships. The use of steel ships, however, forced the naval stores industry to explore new markets for their products, and today the major uses are centered in the retail sales, chemical and pharmaceutical, and paper and paper sizing industries.

Naval stores industry may be subcategorized into three separate subindustries depending on the method of harvesting and product production; they are (1) gum naval stores, (2) wood naval stores, and (3) sulfate pulping.

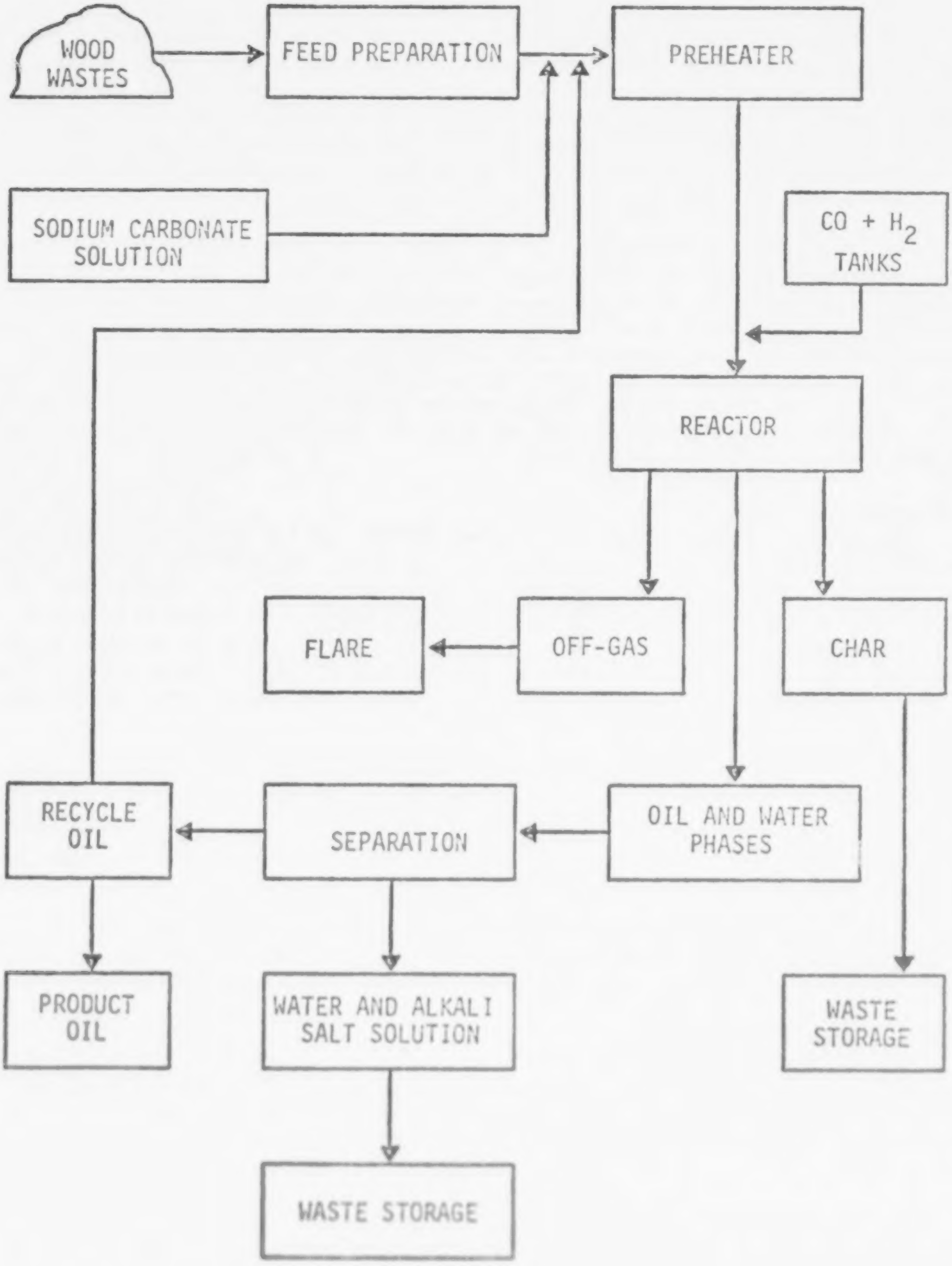

WOOD WASTES
FEED PREPARATION
PREHEATER
SODIUM CARBONATE SOLUTION
CO + H2 TANKS
REACTOR
FLARE
OFF-GAS
CHAR
RECYCLE OIL
SEPARATION
OIL AND WATER PHASES
PRODUCT OIL
WATER AND ALKALI SALT SOLUTION
WASTE STORAGE
WASTE STORAGE

Figure 36. Simplified flowsheet for the Albany pilot plant.(129)

Gum Naval Stores--

The gum naval stores are produced from the crude gum (oleoresin) collected from chipped or wounded slash and southern long leaf pines. The gum contains principally turpentine and resin in proportions and with a composition typical of that shown in Table 63. The gum is collected every 1 to 2 weeks and transferred to a central plant where it is steam-distilled, either batch-wise or continuously to produce a variety of products, turpentine, wood rosin, and tar.

The wounding and harvesting of the tree represents the oldest and most labor-intensive method of extracting the oleoresin feedstock. The use of chemical treatments (such as paraquot solutions) applied to the surface of the tree near the wound have increased the production of resin; however, the characteristically low pay scale and unappealing working conditions have encouraged a migration of the labor force away from this industry. At present, the gum naval stores represent the least productive of the three naval stores industries and in the foreseeable future cannot be regarded as particularly viable sources of fuel.

Wood Naval Stores--

The wood naval stores industry uses the stumps and other resinous waste wood from cut-over pine forest. The wood is sometimes allowed to age for a few years to permit the non-resinous parts to rot away after which time it is hogged and shredded and introduced into the steam-heated extraction vessel. A petroleum-base solvent (so selected for its ease of separation from turpentine) contacts the wood chips and extracts the rosin and terpene oils. The hot extract is drained off and fractionally distilled to recover the solvent, rosin, and terpene oils.

The chips are steamed once more to recover any residual solvent and are used as fuel or marketed as feedstock for particle board. From 0.9 metric ton (1 ton) of wood, about 180 kg (400 lb) of rosin, 30 liters (8 gallons) of turpentine, 13 liters (3.5 gallons) of pine oil, and 5.6 liters (1-5 gallons) of monoacylic hydrocarbons are produced.

The wood naval stores industry represents the second largest of the tree industries in terms of total turpentine and rosin production. One of the major products of this industry is pine oil which is not found in gum.

Sulfate Pulping Industry--

The off-gases and liquid residue from the sulfate (or kraft) pulping process are now the principal sources of turpentine and a major source of rosin (as tall oil rosin). This method for naval stores production is the most recent and was not practiced on a commercial scale until after World War I.(132)

The relief gases from the digesters for sulfate pulp contain turpentine and pine oil. When the gases are condensed, the crude oil in quantities of 8 to 40 liters per metric ton (2 to 10 gallons/ton) floats to the top. The oil contains 50 to 60 percent turpentine and 10 to 20 percent pine oil which are separated by fractional distillation. The resulting turpentine contains offensive mercaptans which are removed by a hypochlorite solution of ethylene diamine.

TABLE 63. THE COMPOSITION OF OLEORESIN

Commercial Fraction of Oleoresin	Per Cent of Oleoresin	Compound	Per Cent of Compound in Commercial Fraction	Per Cent of Compound in in Oleoresin
Turpentine	20	α-Pinene	60	12
		β-Pinene	35	7
		Low-Boiling Matter	0.07	0.01
		High-Boiling Matter	5	1
Rosin	80	Levopimaric Acid	32	26
		Neoabietic Acid	18	14
		Abietic Acid*	18	14
		Dextropimaric	7	6
		Isodextropimaric	7	6
		Dehydroabietic Acid*	4	3
		α-Dihydroabietic	4	3
		Resenes	10	8

*There remains some doubt as to the presence of these compounds as primary constituents of oleoresin. See Simonsen, F. L., The Terpenes, Volume III, University Press, Cambridge, 1947, pp. 375-458.

The tall oil or liquid rosin is obtained upon acidification of the digestor liquor. The tall oil soap is skimmed from the top of the liquor and fractionated to produce turpentine, pitch, fatty acids, and rosins.

Product Application as a Fuel--

Most of the naval stores products, tall oil, pitch, and pine oils are combustible but are viscous liquids and, as is, are not amenable for use in commercial liquid-fueled boilers or combustors. The turpentine has a heating value about 8000 kal/kg (15,000 Btu/lb) and could be considered as a possible supplemental fuel. The turpentine could probably be best suited as a boiler fuel rather than as an automotive fuel due to its volatilizing characteristics. If the turpentin were hydro-cracked into smaller, hydrogenated molecules, it might serve as a suitable feedstock to a refinery; this would be an extremely cost intensive method, however, to manufacture gasoline. In view of the market value of turpentine as a solvent and chemical feedstock, its availability and its high cost per Btu, it cannot be regarded as a likely candidate for a supplementary fuel without major technological breakthroughs and complete modernization of the industry. Paraquot stimulation, as noted earlier, has increased naval stores products in growing trees substantially. Comparable process technology improvements will also be required. Finally, competition with pulp and paper and wood products industries for feedstock is a likely source of economic difficulties.

Charcoal Production

Charcoal is commonly manufactured by low temperature distillation, or pyrolysis, of hard wood wastes. The distillation of hard wood has been practiced for decades, originally as a method for producing acetic acid, acetone, and methanol (wood alcohol). The details of the manufacturing process are technologically well known and are not presented in detail in this study. Predried wood waste (sawdust, chips, etc.) is continuously fed into the reactor or kiln. At a temperature of about 400 C (750 F) and in an oxygen-deficient atmosphere, the wood is pyrolyzed to a rich gas and charcoal solid is continuously withdrawn from the reactor. The product gas is cooled to condense recoverable acids, alcohols, and tars. The charcoal product, accounting for about 25 percent of the dry wood feed, is either sold as is for a reducing agent or a purifying medium, or briquetted primarily for use as a recreational fuel. Typical yields from the distillation of 1.8 metric tons (2 tons) of raw hard wood are presented in Table 64.(133) As a recreational fuel, charcoal is attractive for its non-smoking properties and its high heating value, 7200 - 7700 kcal/kg (13,000 to 14,000 Btu/lb).

TABLE 64. TYPICAL DISTILLATION YIELDS FROM 1.8 METRIC TONS (2 TONS) OF HARDWOOD(133)

Item	Percent Yield
Charcoal	25.2
Crude Methanol	1.9
Autic acid or equivalent	2.9
Tar, oil	5.0
Gas	18.3
Water, etc.	46.7
	100.0

The use of other cellulosic materials as a feedstock for the manufacture of charcoal has been investigated in recent years, and bagasse, peanut shells, agricultural wastes, and soft wood waste have all been utilized as feedstock in pilot-scale evaluations.(134,135) The results of the evaluations indicate that these types of biomass waste are suitable charcoal feedstocks and produce a charcoal with a heating value of 6100-7200 kal/kg (11,000-13,000 Btu/lb).(135)

No information was available on environmentally related problems with the waste streams generated from the charcoal manufacturing process. The entire process involves drying, pyrolysis, condensation, separation and combustion and should be expected to produce generically the same solid (ash and residue charcoal), liquid (condensed water and organic chemicals), and gases (pyrolysis, drying and combustion gas) as a pyrolysis process operating with wood feed.

PRIMARY BIOCHEMICAL CONVERSION PROCESS

Methane Production by Anaerobic Digestion

Anaerobic digestion is a biological process by which bacteria converts organic material to gaseous products in the absence of oxygen. It has been used as a method of waste treatment for over 100 years. Anaerobic digestion is used primarily for liquid waste treatment and more recently has been applied to disposal of urban refuse. The conversion of wastes into an energy source has been a recent adaptation of the process.

If the complexity of the biochemical reactions is ignored, anaerobic digestion is a simple process. It occurs at lower rates and temperatures than thermochemical processes and therefore is less energy intensive. Anaerobic digestion is usually considered to occur in three steps. In the first step, complex organics are hydrolyzed to simpler organics. These compounds are then converted to volatile fatty acids, carbon dioxide, hydrogen, and the cell mass of acid-forming bacteria. In the last step, methane-forming bacteria convert the simple acids formed in the second step to methane, carbon dioxide, and methanogenic organisms. The rate limiting step in this process is the slow growth rate of the methane-forming bacteria.

Microbiology--

Although all biomass feedstocks contain the major substrates necessary for the growth of the general microbial population, the amounts and types of substrates vary with the composition of each feedstock. Therefore, different feedstocks support the growth of different types of bacteria.

The nonmethanogenic bacteria are a widely diverse group of anaerobic and facultative bacteria. Obligate anaerobic bacteria appear to be mainly responsible for acid production. A review of the counts and isolations of the highly specialized group of methanogenic bacteria is given by Hobson, et al.(136)

An outline of the basic reactions involved in anaerobic digestion is shown in Figure 37.

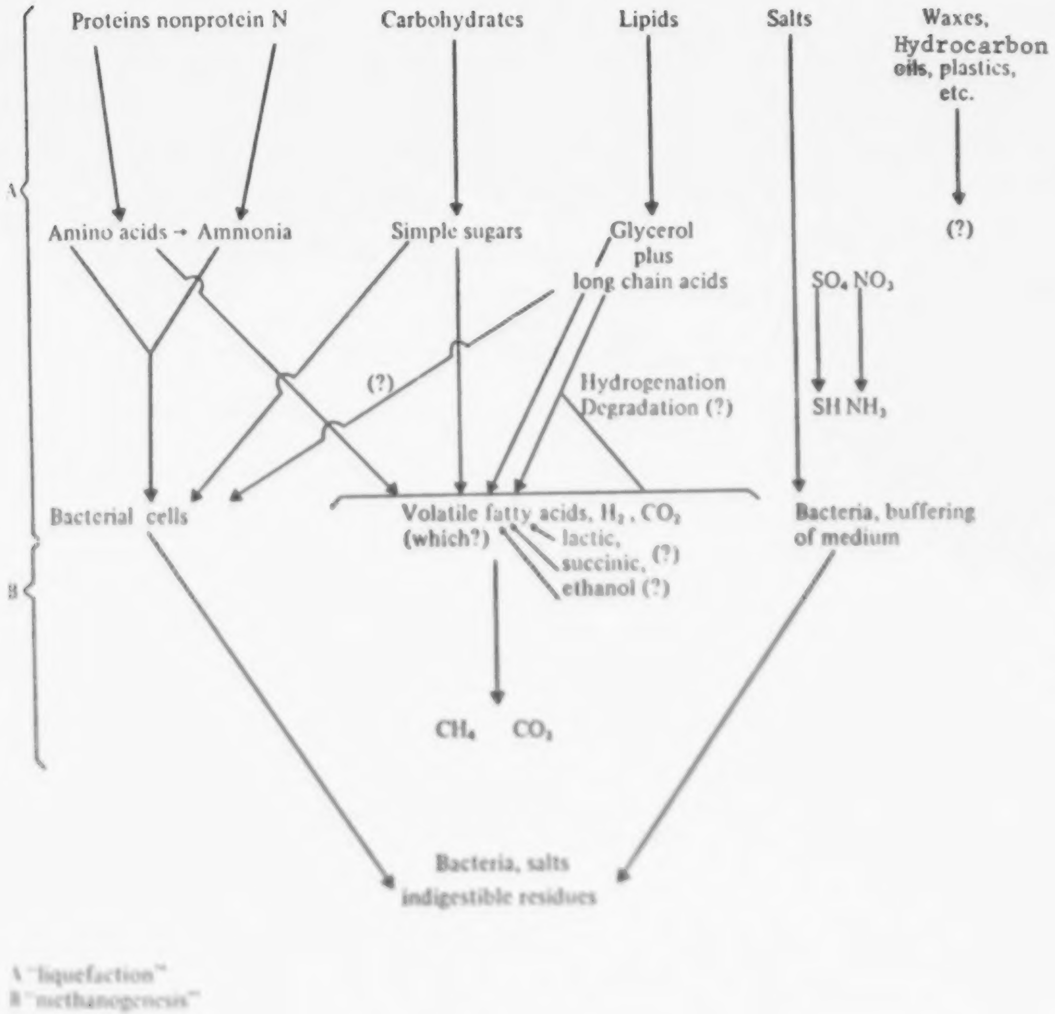

Proteins nonprotein N
Carbohydrates
Lipids
Salts
Waxes, Hydrocarbon oils, plastics, etc.
A
Amino acids → Ammonia
Simple sugars
Glycerol plus long chain acids
(?)
SO_4 NO_3
(?)
Hydrogenation Degradation (?)
SH NH_3
Bacterial cells
Volatile fatty acids, H_2, CO_2 (which?)
lactic,
succinic, (?)
ethanol (?)
Bacteria, buffering of medium
B
CH_4 CO_2
Bacteria, salts indigestible residues
A "liquefaction"
B "methanogenesis"

Figure 37. Reactions occurring during anaerobic digestion.(130)

Acetate is generally regarded as the major substrate for methane formation. Hydrogen plus carbon dioxide are also substrates for methane formation. The fermentation of carbohydrate to acetate, hydrogen, and carbon dioxide is represented by the following reactions.

$$\begin{array}{c} C_6H_{12}O_6 \rightarrow 2CH_3COCOOH + 2H_2 \\ 2\ CH_3COCOOH + 2H_2O \rightarrow 2\ CH_3COOH + 2H_2 + 2CO_2 \\ 4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \\ 2\ CH_3COOH \rightarrow 2CH_4 + 2CO_2 \\ \hline C_6H_{12}O_6 \rightarrow 3CH_4 + 3CO_2 \end{array}$$

Critical Variables--

The critical variables involved in the maintenance of a proper environment are (1) temperature, (2) anaerobic conditions, (3) nutrients, (4) pH, and (5) absence of toxic materials.

Two optimum temperature levels have been established for anaerobic processes: mesophilic (30 C to 37.5 C) and thermophilic (49 C to 60 C). Operation of a digester in the thermophilic range results in increased rates of reaction, lower retention time, and a smaller required volume. Currently, most sewage sludge digesters operate at the mesophilic level because heat requirements to maintain the thermophilic temperature level are high. Since more methane can be produced at the higher temperature, this increased production must be weighed against the energy requirements. There has also been speculation that digesters are more unstable at thermophilic temperatures.(137)

While anaerobic digestion can occur in the pH range of 6.6 to 7.6, the optimum pH is from 7.0 to 7.2. Below pH 6.2, the acidic conditions become toxic to the methane forming bacteria. An increase in the volatile fatty acids produced by the acid-forming bacteria can inhibit the methane production because of the reduced pH.

Non-anaerobic or aerobic conditions in the digester cause instability and, in time, complete failure.(138)

The raw material must be free of toxic substances. High concentrations of salts, ammonia, sulfides, heavy metals, or other toxic organics may cause instability or complete failure of the digester.

One-Stage Digester--

A conventional single-stage digester employs one tank for all phases of digestion. The feed is introduced either periodically or continuously and mixed with the digester contents. The effluent, which contains microorganisms, residual feed, and intermediate products is withdrawn at the same rate.

As the retention time is reduced, larger quantities of bacteria are removed. The limiting retention time occurs when more of the bacteria are removed from the tank than are reproduced. The limiting retention time is usually three to five days. For increased reliability and practical control, retention times of ten to thirty days are normally used.

Gas is produced continuously from the digestion tank. The gas is processed to remove acid gases (chiefly CO_2 and H_2S), dried, and compressed to standard pipeline pressure.

The effluent from the digester is dewatered and the separated water is either recycled or sent to a sewage treatment plant. The residual sludge represents a disposal problem. Typically the sludge is disposed of by landfill, lagooning or incineration. The suitability of the residue as a fertilizer varies with the quantity of nitrogen, phosphorus, and other chemicals present in the cake. Their presence depends on the type of raw material used in the feed.

Two-Stage Digester--

One variation of anaerobic digestion is the two-stage digester. A typical system is illustrated in Figure 38. In this system the acidogenic reaction can be separated from the methanogenic reaction. The separate reactors are operated in series.

The separation of the two stages could be done on a large scale only by differing the retention times of the two tanks. Using an easily digestible material as the feedstock to the first digester shortens the required retention time in the first stage. A longer retention time in the second stage allows the methanogenic bacteria to grow on the effluent from the first stage.

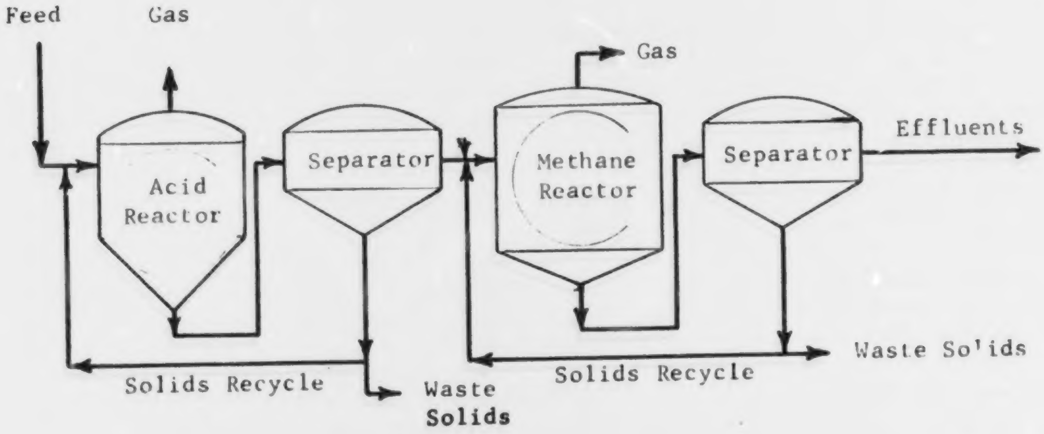


Figure 38. Two-stage anaerobic digestion.

The advantages of a two-stage system are (1) the increased concentration of methane and therefore higher Btu content of the gas, (2) the capability of maintaining the optimum environmental conditions for each stage, (3) reduction in reactor volume, and (4) increased stability of the reactors.(139)

The major disadvantages of a 2-stage system are the increased operating costs over a single-stage system due to heating requirements(139) and probably higher investment costs. Data are also sparse on operating characteristics of these systems, and the data which do exist are at laboratory scale.

High Rate Digester--
The high rate digester is a single-stage system with recycle of bacteria to increase the efficiency of the system. An example of bacterial cell recycle is an activated sludge system. This method is applicable to dilute wastes at high flow rates. Mechanical separation of the active bacteria from the partially degraded solids increases the time for the reattachment of the bacteria to the solids upon return to the digester. Therefore, a recycle system is not suitable for wastes of high solids content which are not readily degradable, because the required high solids concentration in the reactor will probably make mixing power requirements prohibitive.

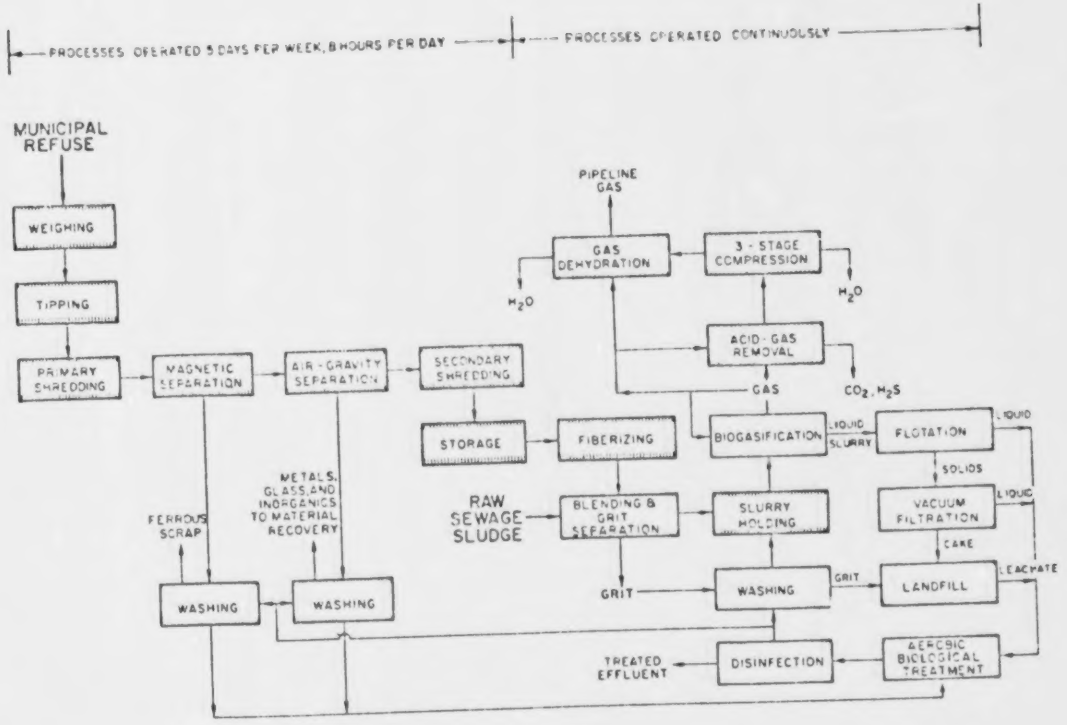
Feed Materials--
Anaerobic digestion is applicable to a variety of feed materials which can be characterized by the following factors: (1) method and cost of collection; (2) methane yield from digestion; and (3) sludge characteristics.

Raw sewage and sewage sludge--Sewage sludge is the concentrated waste obtained after various sewage treatment steps and typically contains 3 to 6 percent solids. The composition of the gas produced from digestion of sewage is 65 to 70 percent methane, 25 to 30 percent carbon dioxide, and small quantities of hydrogen, nitrogen, and other gases. Total gas production ranges between 0.5 and 0.75 cu m per kg (8 and 12 cu ft per pound) of volatile solids.

Refuse--The composition of urban refuse has been analyzed in numerous studies. Gas production of a typical sample is approximately 0.4 cu meters per kg (6 cu ft per pound) of volatile solids with methane composing 50 to 60 percent of the gas. Gas production depends primarily on the quantity and form of cellulose present in the refuse. Refuse is deficient in the necessary nutrients which must be supplied to the system either by mixing with sludge or other nutritious raw material.

The Biogas Process, developed by IGT, is a continuous anaerobic digestion system designed to process municipal refuse and sewage sludge. The process is in the pre-pilot plant stage of development. Large-scale units (over 900 metric tons/day) have been designed, but not built by the Institute of Gas Technology.

The unit operations involved in the process are particle-size reduction, separation of the inorganics, biological gasification, and gas cleaning. Figure 39 is a block diagram of the Biogas Process.



PROCESSES OPERATED 5 DAYS PER WEEK, 8 HOURS PER DAY
PROCESSES OPERATED CONTINUOUSLY
MUNICIPAL REFUSE
WEIGHING
TIPPING
PRIMARY SHREDDING
MAGNETIC SEPARATION
AIR-GRAVITY SEPARATION
SECONDARY SHREDDING
STORAGE
FIBERIZING
RAW SEWAGE SLUDGE
BLENDING & GRIT SEPARATION
GRIT
FERROUS SCRAP
WASHING
METALS, GLASS, AND INORGANICS TO MATERIAL RECOVERY
WASHING
PIPELINE GAS
GAS DEHYDRATION
H_2O
3-STAGE COMPRESSION
H_2O
ACID-GAS REMOVAL
CO_2, H_2S
GAS
BIOGASIFICATION
LIQUID SLURRY
FLOTATION
LIQUID
SOLIDS
VACUUM FILTRATION
LIQUID
CAKE
SLURRY HOLDING
WASHING
GRIT
LANDFILL
LEACHATE
TREATED EFFLUENT
DISINFECTION
AEROBIC BIOLOGICAL TREATMENT

Figure 39. Block diagram of the biogas process.(140)

The incoming refuse is shredded to 6-inch nominal size before magnetic and air separation of the ferrous and non-ferrous metal scrap. Additional shredding of the organic fraction is necessary to reduce the partial size for efficient digestion. The shredded refuse is stored and measured quantities are withdrawn for further shredding to minus 20 mesh. The material is blended with sewage sludge, separated from heavier particles which are washed and fed to a holding tank.

The refuse-sludge mixture is pumped to heated (approximately 35 C) digestion tanks which are mixed. Detention times of approximately 12 days are anticipated. Raw gas from the digesters is processed to remove acid gases which are sent to a sulfur recovery plant. The product gas is dried and compressed for pipeline distribution.(140)

A material balance of the process for a nominal plant size of 900 metric ton/day (1000 t/d) is detailed in Figure 40. Approximately 39 percent of the solids are gasified, 31 percent are disposed of as sludge, and 1 percent are removed in the liquid effluent. The BOD concentration of the liquid stream is approximately 500 mg/l. The remaining 29 percent of the entering solids are recovered as saleable scrap metal or glass.(141)

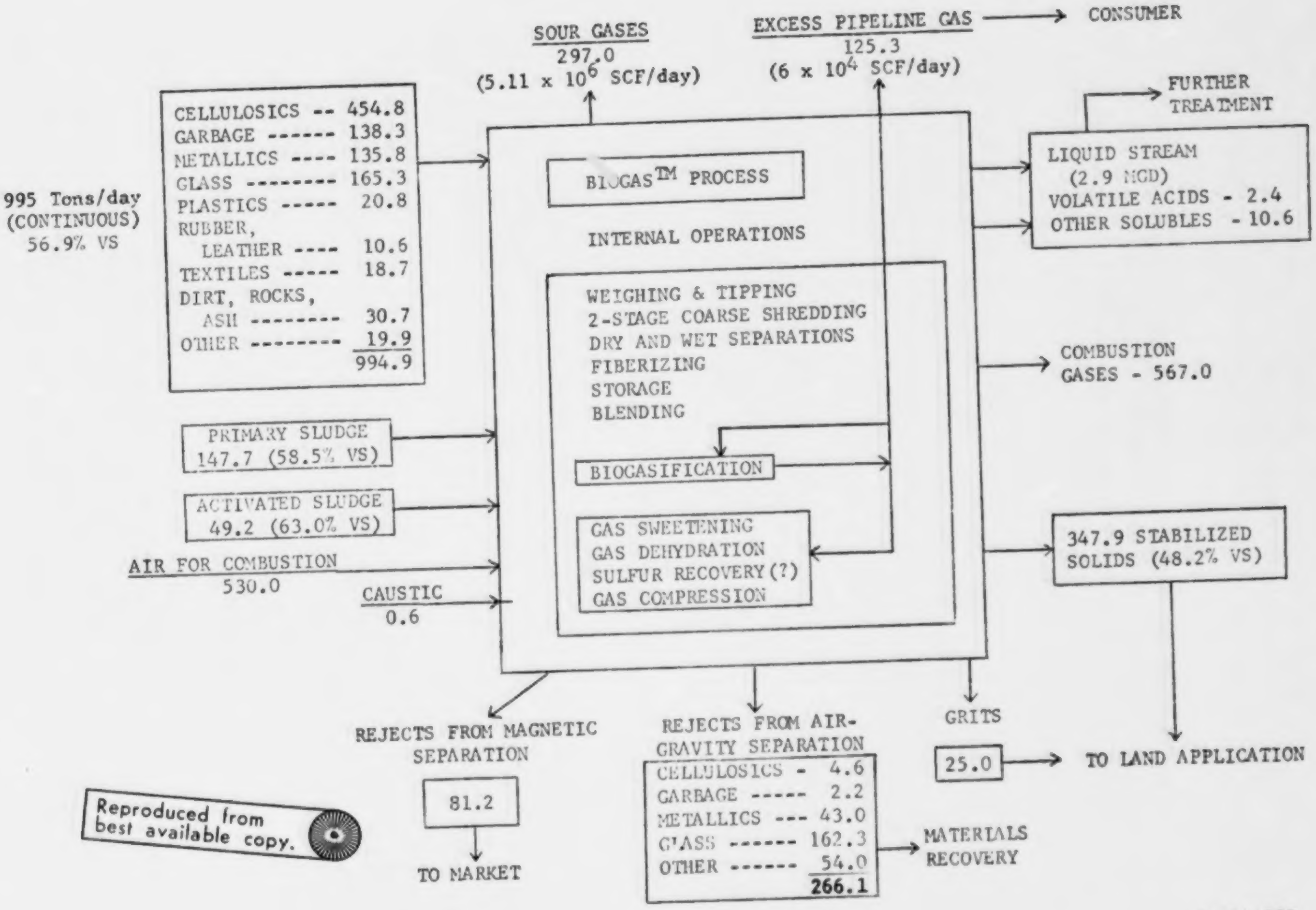
The Dynatech anaerobic digestion process was developed to process municipal refuse and sewage sludge. The design of the system is similar to the design described for the Biogas Process. Preliminary designs and cost estimates of a pilot plant (1.5 metric tons/day) and a commercial-scale plant (900 metric tons/day) have been completed.

A material balance of the system based on 900 metric tons/day is calculated in Figure 41.(142)

Based on laboratory work done by John T. Pfeffer of the University of Illinois, a thermophilic anaerobic digestion system was developed. The digester temperature is 60 C. The preprocessing system design is similar to the previously described refuse digesting systems.(144) A conceptual flowsheet is diagrammed in Figure 42.

Agricultural wastes--Animal waste (including pig, cattle, poultry, and sheep wastes) and other farm wastes such as corn cobs, straw, grasses, and vegetable wastes have been investigated as sources of high Btu-gas from anaerobic treatment processes. These investigations have been limited to laboratory experiments from which a number of large-scale plants have been conceptualized.(145,146,147) The major deterrent to large-scale plants is the economic restrictions of collection and transportation of farm wastes.

Feed lots provide a large quantity of concentrated waste material which is relatively easy to collect. Approximately 0.3 cu m per kg (5 cu ft of gas per pound) of volatile solids is produced. Methane content is about 50 percent. Different types of animals produce manures which vary in the amount of energy content. The more thoroughly the animal digests its own food, the less energy available for methane generation by anaerobic digestion.


SOUR GASES
297.0
(5.11 x 10^6 SCF/day)
EXCESS PIPELINE GAS
125.3
(6 x 10^4 SCF/day)
CONSUMER
FURTHER TREATMENT
995 Tons/day
(CONTINUOUS)
56.9% VS
CELLULOSICS -- 454.8
GARBAGE ------ 138.3
METALLICS ---- 135.8
GLASS -------- 165.3
PLASTICS ----- 20.8
RUBBER, LEATHER ---- 10.6
TEXTILES ----- 18.7
DIRT, ROCKS, ASH -------- 30.7
OTHER -------- 19.9
994.9
BIOGAS™ PROCESS
INTERNAL OPERATIONS
WEIGHING & TIPPING
2-STAGE COARSE SHREDDING
DRY AND WET SEPARATIONS
FIBERIZING
STORAGE
BLENDING
BIOGASIFICATION
GAS SWEETENING
GAS DEHYDRATION
SULFUR RECOVERY (?)
GAS COMPRESSION
LIQUID STREAM
(2.9 MGD)
VOLATILE ACIDS - 2.4
OTHER SOLUBLES - 10.6
COMBUSTION GASES - 567.0
PRIMARY SLUDGE
147.7 (58.5% VS)
ACTIVATED SLUDGE
49.2 (63.0% VS)
AIR FOR COMBUSTION
530.0
CAUSTIC
0.6
347.9 STABILIZED SOLIDS (48.2% VS)
REJECTS FROM MAGNETIC SEPARATION
81.2
TO MARKET
REJECTS FROM AIR-GRAVITY SEPARATION
CELLULOSICS - 4.6
GARBAGE ----- 2.2
METALLICS --- 43.0
GLASS ------ 162.3
OTHER ------ 54.0
266.1
MATERIALS RECOVERY
GRITS
25.0
TO LAND APPLICATION
B-34-495

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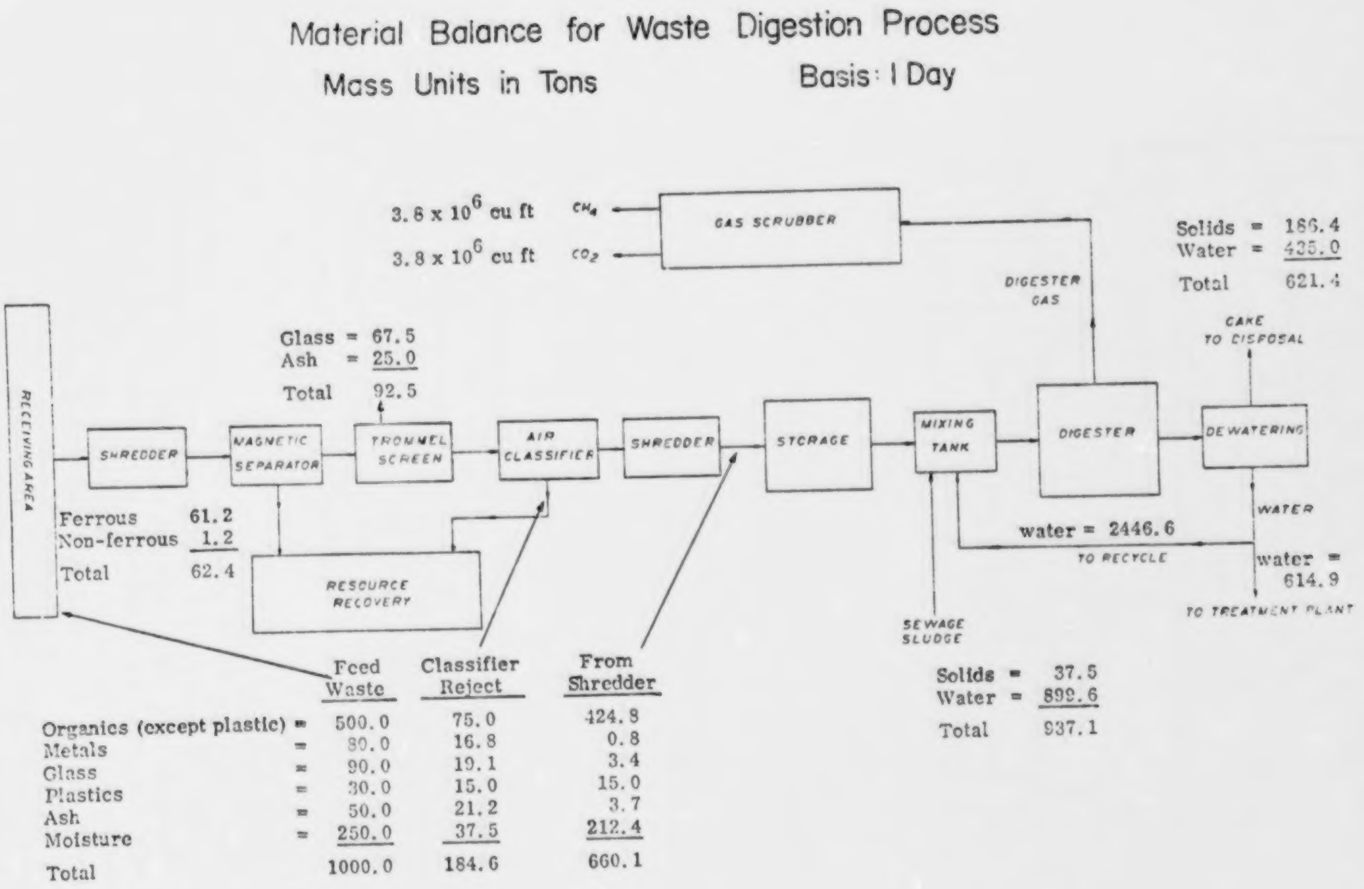
(ALL FIGURES ARE IN TONS/DAY UNLESS INDICATED OTHERWISE)

Figure 40. Mass balance summary for a 1000 ton/day biogas plant.(141)


Material Balance for Waste Digestion Process
Mass Units in Tons
Basis: I Day
3.8 x 10^6 cu ft
CH_4
3.8 x 10^6 cu ft
CO_2
GAS SCRUBBER
DIGESTER GAS
RECEIVING AREA
SHREDDER
MAGNETIC SEPARATOR
TROMMEL SCREEN
AIR CLASSIFIER
SHREDDER
STORAGE
MIXING TANK
DIGESTER
DEWATERING
RESOURCE RECOVERY
CAKE TO DISPOSAL
WATER
water = 2446.6
TO RECYCLE
SEWAGE SLUDGE
TO TREATMENT PLANT

Glass = 67.5
Ash = 25.0
Total 92.5

Ferrous 61.2
Non-ferrous 1.2
Total 62.4

Solids = 186.4
Water = 435.0
Total 621.4

water = 614.9

Solids = 37.5
Water = 899.6
Total 937.1

	Feed Waste	Classifier Reject	From Shredder
Organics (except plastic) =	500.0	75.0	424.8
Metals =	80.0	16.8	0.8
Glass =	90.0	19.1	3.4
Plastics =	30.0	15.0	15.0
Ash =	50.0	21.2	3.7
Moisture =	250.0	37.5	212.4
Total	1000.0	184.6	660.1

Figure 41. Material balance for waste digestion process.(142)

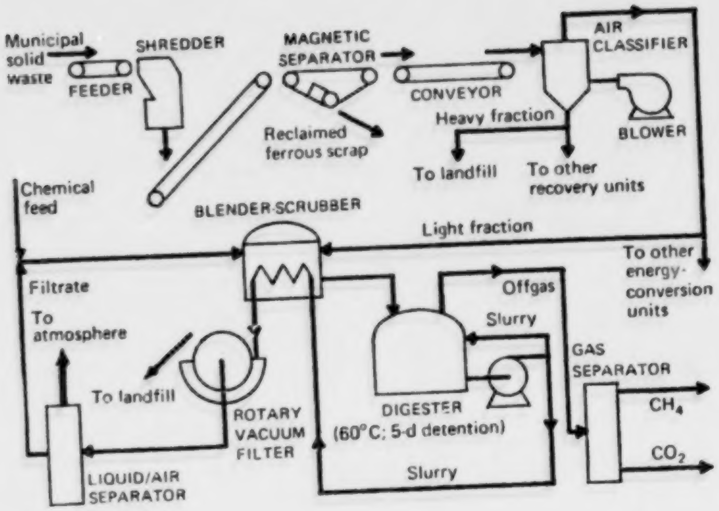

Municipal solid waste
FEEDER
SHREDDER
MAGNETIC SEPARATOR
Reclaimed ferrous scrap
CONVEYOR
AIR CLASSIFIER
BLOWER
Heavy fraction
To landfill
To other recovery units
Chemical feed
BLENDER-SCRUBBER
Light fraction
To other energy-conversion units
Filtrate
To atmosphere
To landfill
ROTARY VACUUM FILTER
Offgas
Slurry
DIGESTER
(60°C; 5-d detention)
GAS SEPARATOR
CH_4
CO_2
Slurry
LIQUID/AIR SEPARATOR

Figure 42. Thermophilic anaerobic digestion system.(143)

Laboratory experiments have shown that manures must be collected and digested immediately after excretion to prevent destruction of the volatile solids.

Residual digester solids have potential value as a fertilizer or feed material.

Algae--Few actual results have been obtained on the digestion of algae, but methane yields are expected to be in the same range as grass clippings, or approximately 0.4 cu m per kg (7.0 cu ft per pound) volatile solids of 70 percent methane gas. One possible combination of feed materials which has been suggested is the growing of algae in ponds fed by sewage, which acts both as a nutrient source and digestible material. Residual material from the digester would have good nutrient value and would be suitable as a fertilizer supplement.

Anaerobic Process Concept Comparison--

It is clear from the work of many investigators that the primary constraint which must be overcome to commercialize anaerobic digestion in a significant sense is the high capital cost associated with long digester residence times for cellulose feedstock. Process developers have taken two routes to achieve this objective: high-rate, single-stage systems with feed pretreatment and solids recycle; and two-stage systems with interstage solid recycle. Both concepts have a common problem. Developers are designing their systems at very high solids concentrations in the reactors. In the small-scale digesters where process development is proceeding, maintenance of these concentration levels is not difficult and is not particularly consumptive of mixing power. However, experience in the pulp and paper and municipal solid waste industries suggest that power requirements for large-diameter vessels at concentration levels of six percent and greater scale very unfavorably. It appears that most developers have sized their mixing power requirements for large systems based on either sewage sludge digestion practice (a considerably different solid than that which predominates with the majority of biomass feedstocks) or as a direct function of vessel diameter. The above-noted industrial practice at high solids concentrations suggests that the diameter raised to the second or third power is more appropriate. If this industrial practice noted proves transferable, digesters being designed on the simpler bases will prove to be grossly underpowered and fail at design conditions. Alternatively, they may be run at reduced feedstock throughout and lower solids concentration, with very serious consequences relevant to net energy production.

The high-rate, single-stage digestion systems are attractive because of their inherent simplicity. Likewise, they are only a first-order extension of existing technology. However, because the methanogenic and acidogenic cultures are mixed, the product gas contains only about 50 percent methane. Removal of approximately one-half of the stream in an acid gas removal system may be economically prohibitive.

Secondarily, some research is proceeding, using caustic soda as a pre-treatment agent, to allow more rapid solubilization of the cellulose in the feedstock. From strictly process considerations, this is advantageous. However, it must be recognized that the ultimate sink for the spent sodium ion is the process water effluent, where it appears as total dissolved solids (TDS). It can be removed from this stream with only the greatest difficulty, in essence, requiring desalination technology. Furthermore, for certain feedstocks, notably manures and kelp with high salt contents, the use of caustic with its associated TDS load may be impractical.

The alternative is a more radical departure from the state-of-the-art, the two-stage system. It is beyond question more complex, and the interrelation of the two stages is only poorly understood. In fact, there are notable experts who claim the system is inoperative because the entire process requires synergetics activity between acidogenic and methanogenic species. However, this latter point is based on too literal an interpretation of the two-stage concept. While the first stage is likely to be almost completely acidogenic, with CO_2 concentration in the range 90-95 volume percent, the second stage will likely contain both methanogenic and acidogenic organisms, with the acidogenic at considerably lower concentration than in single-stage systems.

The convincing argument to show that a second-stage fermentation is plausible is simply waste treatment practices in the distilling and pickling industries, where organic acid wastes abound. In the case of the two-stage digestion system based on cellulosic biomass, it is necessary to maintain the "methanogenic" culture at levels which insure the acid content in the digester is below that toxic to methanogenic species. High concentrations of active micro-organisms are much simpler to maintain in the second stage of a two-stage system as compared to single-stage systems, because the "solids" are not diluted by unreacted biomass, and consequently the higher active concentrations translate into higher volumetric reaction rates.

The two-stage system offers an additional advantage; that is, it effectively performs a gas phase separation. There does not appear to be significantly different total gas production between one- and two-stage systems, based on the meager data available.(139) However, the portion of the total produced in first stage is almost totally CO_2. Consequently, the second stage produces higher methane gas concentration (on the order of 80 volume percent), with the commensurate reduction in acid gas removal requirements. This reduction may amount to as much as 60 percent or more.

While two-stage systems offer several potential advantages, it must be emphasized that the level of development is very much limited, and undoubtedly, additional problems remain to be uncovered. However, it would seem the potential deserves research support.

Enzymatic Hydrolysis

Cellulose is becoming increasingly recognized as an important potential resource. Cellulosic substrates are used in energy production of materials, protein, and essential chemicals. The advantages in the use of enzymes to hydrolyze cellulose instead of acid are: (1) the enzyme is specific for cellulose and does not react with impurities which may be present in the waste; (2) hydrolysis occurs under moderate conditions--therefore, corrosion-resistant vessels are not required, and the products do not decompose under high temperatures; and (3) the glucose product is relatively pure and of a constant composition.(148)

The greatest drawback in the development of a process to convert cellulose to glucose is the slow rate of hydrolysis of untreated substrates. Therefore, increases in yields from enzyme hydrolysis are important in that they can reduce the need for extensive pretreatment.

Cellulose is a polymeric insoluble substance. The physical structure consists of chains which can be interacting or completely non-interacting. Reactivity depends on the degree of interaction of the cellulose chains. Loose chains or free ends are more reactive than highly ordered crystalline cellulose. Most substances contain some reactive free chains, some crystalline cellulose, and a spectrum of partially crystalline cellulose, and so exhibit limited hydrolysis.(149)

Although many fungi and bacteria degrade cellulose, the enzyme system produced by *Trichoderma viride* has been examined most extensively as a source of cellulase enzymes. Cellulase is a complex of enzymes and enzyme-like factors which hydrolyze cellulose. Total hydrolysis is prevented if a complete enzyme system is not present.(148,150)

The moisture content of cellulosic materials must be above a critical level before microbial decomposition begins. For wood, the critical level is the fiber saturation point, usually 24 to 32 percent. Ten percent moisture is adequate for decomposition of cotton. Moisture creates greater accessibility of enzymes and other reagents to the substrate by swelling the cellulytic fibers.

Some metals and metallic salts such as mercury, silver, copper, chromium, and zinc salts contained in the ash of cellulosic materials are in general inhibitory to microbial degradation. On the other hand, manganese, magnesium, cobalt and calcium in the presence of phosphate are stimulatory.

Organic substances, such as ethanol, methanol, ether, and benzene, are present as extraneous materials in cellulosic sources. Some materials promote growth and others, such as soluble carbohydrates, provide substrates for rapid growth of cellulytic microorganisms. Toxic substances, particularly phenols, inhibit growth of microorganisms. Materials which are deposited in the capillary structure reduce the accessibility of the cellulose to the enzymes. Lack of sufficient nitrogen and phosphorus in most cellulose sources reduces the microbial activity.(151)

The physical association of lignin with partially crystalline cellulose prevents degradation by most enzymes and microorganisms. Lignin is a complex aromatic polymer of high molecular weight (Figure 43) which is degraded naturally by enzymes of white-rot fungi. Lignin-degrading enzymes used in conjunction with celluloses represent a possible means of conversion of lignocellulosics. This system is being studied as part of a cooperative program by the U.S. Forest Products Laboratory and the University of Wisconsin.(151,152)

An enzymatic hydrolysis process is being developed at the U.S. Army Natick Laboratories in Natick, Massachusetts. A functional schematic diagram of the process is pictured in Figure 44. A bench-scale integrated laboratory facility has been set up to investigate the process. The equipment is designed to study batch, semi-continuous, and continuous processes. The reaction vessel is 250 liters (66 gallons) and has a capacity between 454 and 1800 kg of cellulose per month (1000 to 4000 lbs per month).

The rate of hydrolysis of a number of cellulose sources is illustrated in Table 65. The rate is slow for crystalline cellulose materials such as cotton or bagasse; however, pretreatment increases the reactivity significantly. Fibers obtained from the Black Clawson hydrapulping process are good sources for hydrolysis, especially after milling.(148)

Wilke has proposed several conceptualized process schemes for enzymatic hydrolysis of cellulose. A flow sheet of a process is shown in Figure 45. Wilke has also made preliminary cost estimates of the system.

Several areas of uncertainty occur in an economic evaluation of enzymatic hydrolysis. It is difficult to determine the value of the waste cellulose material, which includes both the cost of acquisition and preparation. Second, the quantities of enzymes which can be produced by fermentation and recovered for recycle by filtration of the effluent are also uncertain. The rate of cellulose conversion in a continuous system represents the most significant unresolved process uncertainty. This must be answered to determine the cost of disposal of the unconverted fraction. Without this information, reliable assessments of enzymatic hydrolysis of cellulose for comparison with other

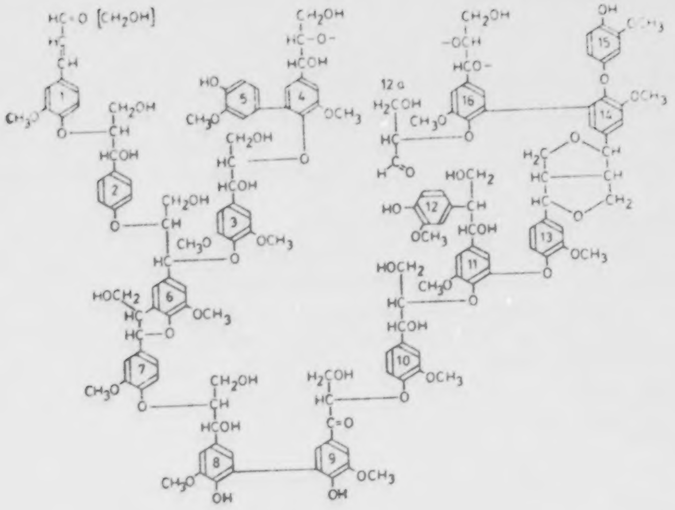


Figure 43. A conceptualized lignin structure.(152)

TABLE 65. ENZYMATIC HYDROLYSIS OF VARIOUS CELLULOSE SOURCES(148)

Substrate	% Saccharification			
	1 hr	4 hr	24 hr	48 hr
Cotton - Fibrous	1	2	6	10
Cotton - Milled	14	26	49	55
Bagaase	1	3	6	6
Bagaase - Milled	14	29	42	48
Black Clawson Hydrapulped Fibers	5	11	32	36
Black Clawson Fibers - Milled	13	28	53	56
Air Classified Municipal Refuse	7	16	25	30
Air Classified Refuse - Milled	13	31	43	57

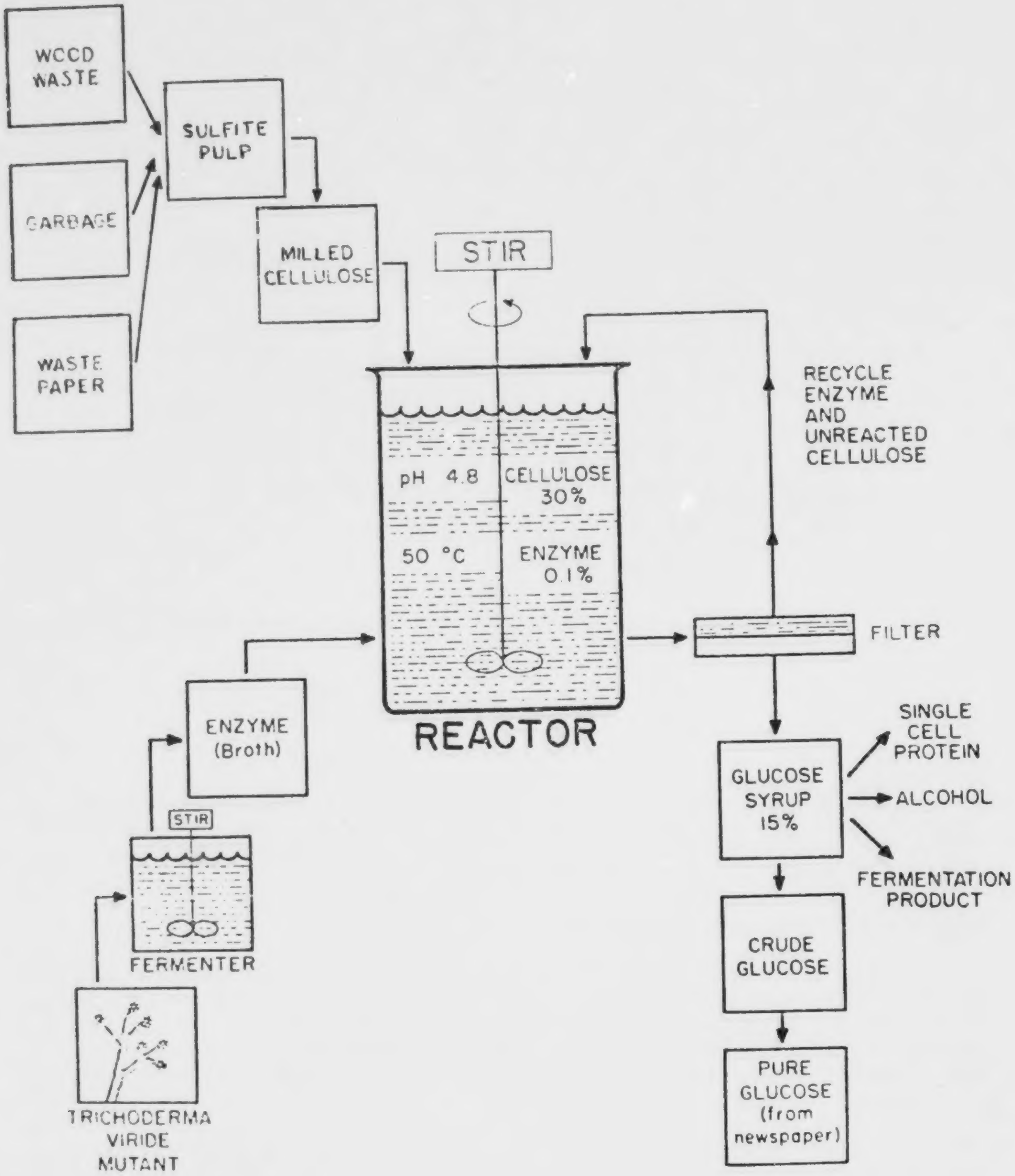

WOOD WASTE
GARBAGE
WASTE PAPER
SULFITE PULP
MILLED CELLULOSE
STIR
RECYCLE ENZYME AND UNREACTED CELLULOSE
pH 4.8
CELLULOSE 30%
50 °C
ENZYME 0.1%
FILTER
REACTOR
ENZYME (Broth)
STIR
FERMENTER
TRICHODERMA VIRIDE MUTANT
GLUCOSE SYRUP 15%
SINGLE CELL PROTEIN
ALCOHOL
FERMENTATION PRODUCT
CRUDE GLUCOSE
PURE GLUCOSE (from newspaper)

Figure 44. Conversion of cellulose to glucose.(148)

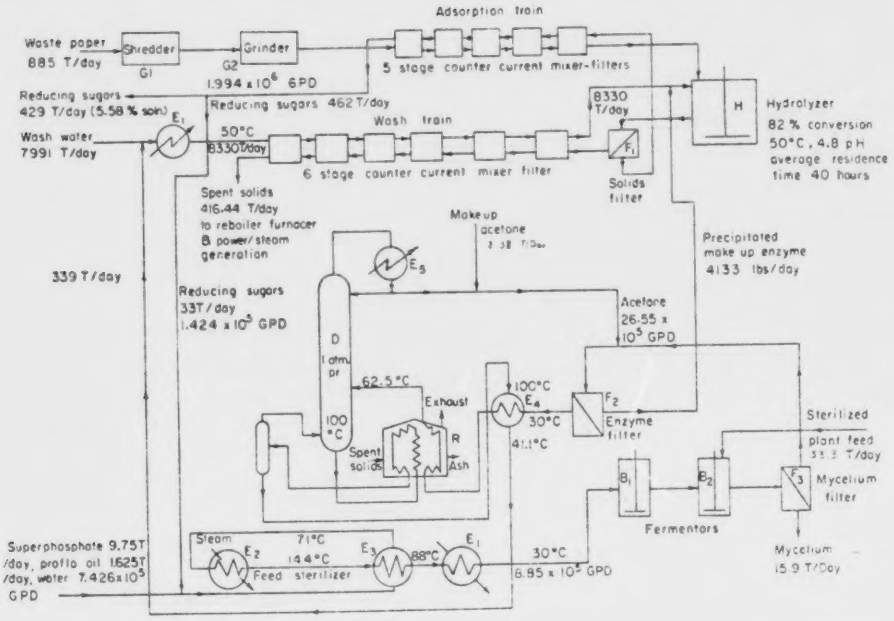

Adsorption train
Waste paper
885 T/day
Shredder
G1
Grinder
G2
1.994 x 10⁶ GPD
5 stage counter current mixer-filters
Reducing sugars
429 T/day (5.58 % soln)
Reducing sugars 462 T/day
E₁
Wash water
7991 T/day
50°C
8330 T/day
Wash train
8330 T/day
F₁
H
Hydrolyzer
82 % conversion
50°C, 4.8 pH
average residence
time 40 hours
6 stage counter current mixer filter
Solids filter
Spent solids
416.44 T/day
to reboiler furnace
& power/steam
generation
Make up
acetone
2.38 T/Day
E₅
Precipitated
make up enzyme
4133 lbs/day
339 T/day
Reducing sugars
33T/day
1.424 x 10⁵ GPD
Acetone
26.55 x
10⁵ GPD
D
1 atm pr
62.5°C
100 °C
Exhaust
R
Spent solids
Ash
100°C
E₄
30°C
41.1°C
F₂
Enzyme filter
Sterilized
plant feed
33.3 T/day
B₁
B₂
F₃
Mycelium filter
Fermentors
Mycelium
15.9 T/Day
Superphosphate 9.75T
/day, proflo oil 1.625T
/day, water 7.426x10⁵
GPD
Steam
E₂
71°C
144°C
Feed sterilizer
E₃
88°C
E₁
30°C
6.85 x 10⁵ GPD

Figure 45. Flowsheet of enzymatic hydrolysis.(153)

methods of treatment cannot be made.(153) Therefore, although enzymatic hydrolysis may prove at some future date to be the more economic hydrolysis method, the scenarios developed in this report will rely on the better established acid hydrolysis process systems.

Biochemical Generation of Hydrogen

It has been demonstrated that a few biological systems produce hydrogen by the direct photolysis of water. The photosynthetic process in some green plants and bacteria can be altered by limiting the quantities of carbon dioxide and oxygen available to the plant to induce hydrogen production. The enzyme system is very sensitive to oxygen, which inhibits the evolution of hydrogen.

Laboratory experiments carried out with Anabaena cylindrica, a blue-green alga, have produced both hydrogen and oxygen from water and light. The reaction is inhibited by nitrogen but insensitive to carbon monoxide.(154) The conversion efficiencies of a system of this type are very low. Although, theoretically, ten percent conversion of solar energy can be achieved by photosynthesis, the conversion efficiency with hydrogen production is much lower. Instead of allowing the evolution of hydrogen and oxygen, Calvin(155) has proposed a photoelectrochemical cell which uses the electrons formed in the reactions to generate a current. This synthetic system would be a means of converting solar energy directly to electricity.

These systems are in the very early stages of development and do not, at this time, represent practical alternate energy sources.

SECONDARY CONVERSION PROCESSES

This section examines the various processes that could potentially be utilized to convert the gas or liquid products generated from primary biomass conversion process into more selective specific fuels or chemicals.

Gas Based Conversion Processes

Methanol Production--

Methanol has been demonstrated as being a satisfactory fuel substitute for applications in automobiles, boilers and gas turbine generators.(156) The advantages cited for methanol over conventional petroleum fuels are the reduced environmental implications associated with its use.

Natural gas is currently the major feedstock for methanol production. Methane is initially processed through a steam reformer to yield CO and H_2 which are subjected to a water-gas reaction to establish the correct molar relationship of approximately 2 to 1. The synthesis gas produced from some pyrolysis processes, however, is rich in CO and H_2 and could potentially serve as a feedstock to a conventional methanol production process. The details of the production of methanol from synthesis gas are established technology and are only highlighted in this report.

The commercial methanol processes may be categorized into two classifications: (1) high pressure (> 100 atm) and (2) low pressure (< 100 atm).

High pressure methanol processing--Most of the earlier methanol production was obtained from the high pressure processing scheme. Silver or copper catalysts are utilized to generate methanol at a pressure of 300 atm and a temperature of 300 C (Figure 46). The conversion of carbon monoxide is low (12-15 percent) and is limited by the characteristics of the catalyst. Moreover, the process is not selective in producing methanol but produces higher alcohols, methyl ethers, and methyl acetate. However, when viewing the resulting methanol as a fuel, the presence of higher alcohols are not objectionable as they increase the heat of combustion. The presence of higher alcohols may also minimize problems associated with phase separation in methanol-gasoline-water systems. With emphasis on the production of a methyl fuel mixture, the Vulcan Manufacturing Company has conceptualized a high pressure process employing longer residence times in the converter and subsequently higher conversions of carbon monoxide; see Figure 47. Vulcan claims this concept produces a methyl product richer in higher alcohols and more suitable as a fuel.(157)

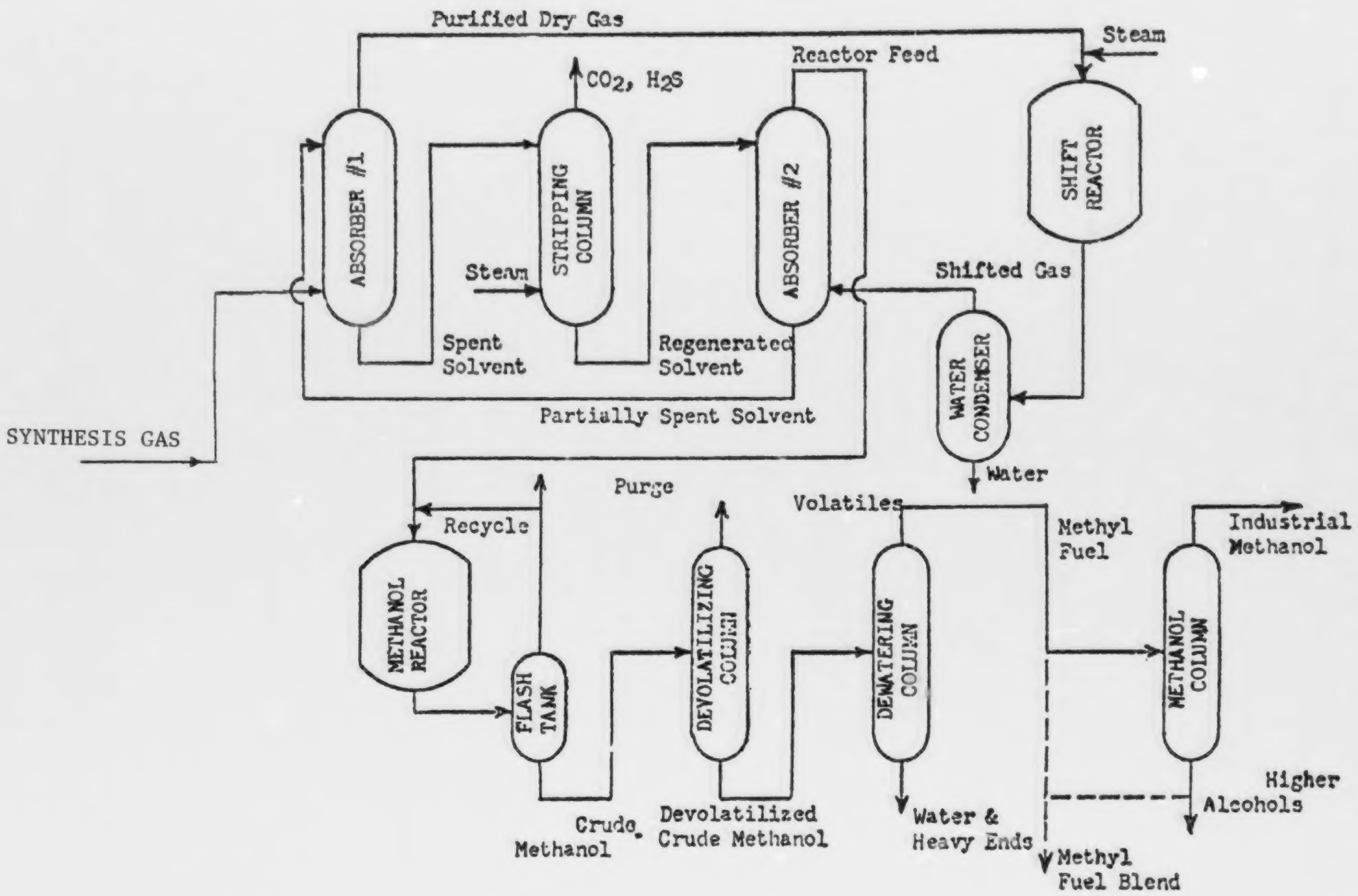

Purified Dry Gas
Steam
Reactor Feed
CO_2, H_2S
ABSORBER #1
STRIPPING COLUMN
ABSORBER #2
SHIFT REACTOR
Steam
Shifted Gas
Spent Solvent
Regenerated Solvent
WATER CONDENSER
Partially Spent Solvent
SYNTHESIS GAS
Water
Purge
Volatiles
Recycle
Methyl Fuel
Industrial Methanol
METHANOL REACTOR
FLASH TANK
DEVOLATILIZING COLUMN
DEWATERING COLUMN
METHANOL COLUMN
Higher Alcohols
Crude Methanol
Devolatilized Crude Methanol
Water & Heavy Ends
Methyl Fuel Blend

Figure 46. Typical high pressure methanol process.

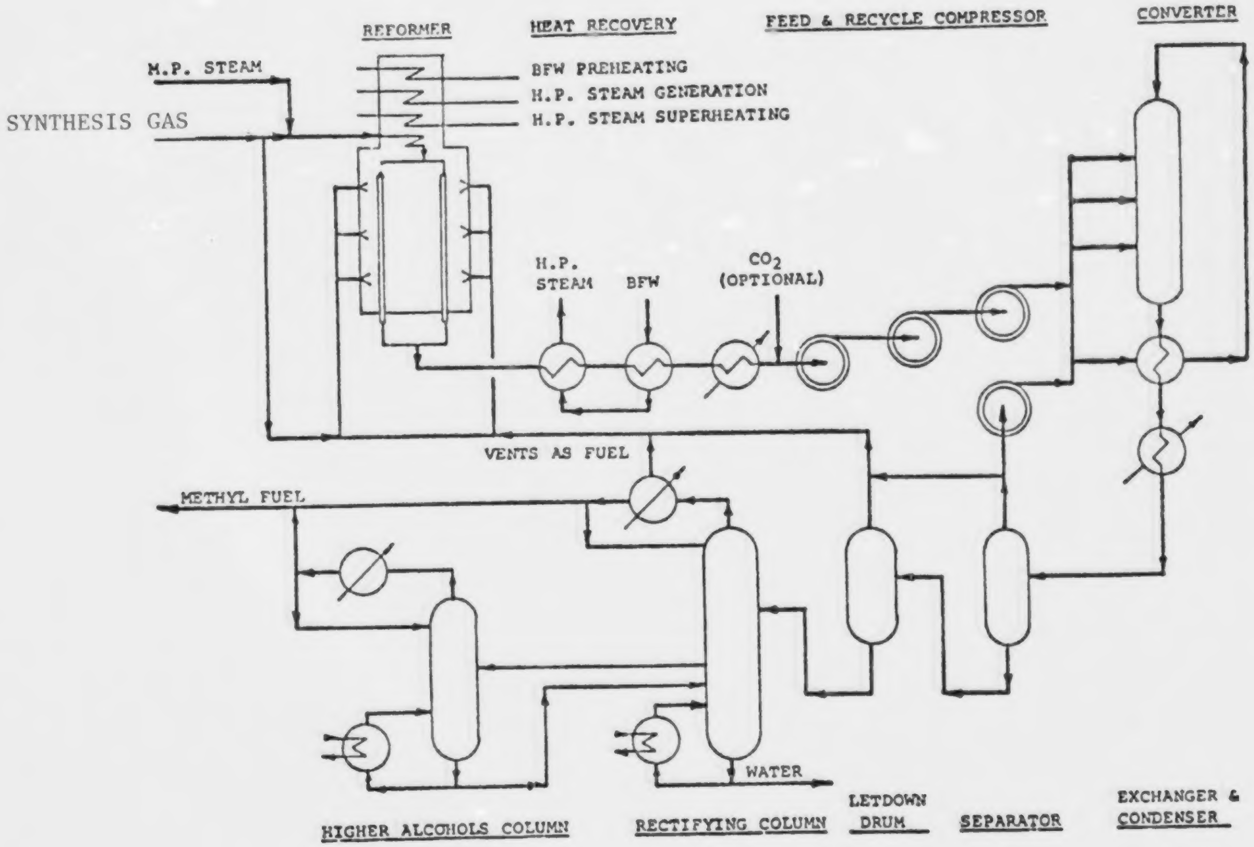

REFORMER
HEAT RECOVERY
FEED & RECYCLE COMPRESSOR
CONVERTER
M.P. STEAM
SYNTHESIS GAS
BFW PREHEATING
H.P. STEAM GENERATION
H.P. STEAM SUPERHEATING
H.P. STEAM
BFW
CO2 (OPTIONAL)
VENTS AS FUEL
METHYL FUEL
WATER
HIGHER ALCOHOLS COLUMN
RECTIFYING COLUMN
LETDOWN DRUM
SEPARATOR
EXCHANGER & CONDENSER

Figure 47. Vulcan methyl fuel process.(157)

Low pressure methanol processing--A major breakthrough in methanol synthesis occurred in the early 1960's when it was discovered that high methanol yields could be obtained at low operating pressures of 50 to 100 atm using a fixed-bed copper-zinc-chromium catalyst. The decrease in pressure resulted in substantially reduced capital, operating and maintenance costs, and, since the mid-1960's, essentially all new methanol plants have been of the low-pressure type.

The low-pressure methanol catalyst has a high selectivity and produces 99.85 percent pure methanol, thus reducing the purification costs. The catalyst is, however, sensitive to sulfur poisoning and limits the concentration of H_2S in the feed stream to 0.5 ppm. Moreover, unlike the catalyst in the high pressure process, the low pressure catalyst cannot be regenerated.

A schematic flow diagram, based on the Imperial Chemical Industries, Ltd., (ICI) low-pressure process is shown in Figure 48.(158) After compression to about 50 atm, the synthesis gas is directed through an absorption sequence for the removal of H_2S and other sulfur compounds. The gas is then sent to a series of guard chambers which hydrogenate the unsaturated compounds, remove any remaining traces of H_2S and chlorine compounds. This sequence of guard chambers protects the water-shift and methanol catalyst from contamination.

In the next step, the water-gas shift reactor employs an iron oxide-chromium oxide type catalyst to convert carbon monoxide and steam to carbon dioxide and hydrogen. The objective is to adjust the hydrogen to carbon monoxide ratio to that desired for the methanol synthesis. The normal temperature range for this reaction is 380-510 C (650-850 F).

Following the water-gas shift reaction, a second absorption train removes excess CO_2 to reduce the load on the methanol reactor and other downstream equipment. The purified gas enters the methanol reactor where at 50 atm and 250 C (480 F) the carbon monoxide and hydrogen are reacted over a catalyst to form methanol. The product is subsequently purified in a devolatilization column and dewatering column and distilled to separate it from the higher alcohols. For use strictly as a fuel, the increased heating value of the heavier alcohols would augment the combustion characteristics of the product alcohol and the final distillation step could be eliminated in favor of forming a methyl fuel blend.

Higher Alcohols--

An alternative to the standard low pressure (50 atm) methanol process is to operate with a less selective catalyst at a higher pressure ($\sim$ 100 atm) with the objective of producing a lower purity methanol at a higher yield and heating value. As operating temperature and pressure of the methanol reactor are increased, by-product formation (namely, methyl ether, methyl acetate, ethanol, and higher alcohols) tends to increase as a result of the non-selectivity. These by-products have higher heating values than methanol and would not only increase the heat of combustion, but as stated earlier, would improve the solubility of methanol in gasoline. Although the moderate pressure processes are currently being marketed and, for natural gas feedstock, show a cost savings in overall plant production, the emphasis is not on by-product formation but rather higher methanol yields. There is, in fact,

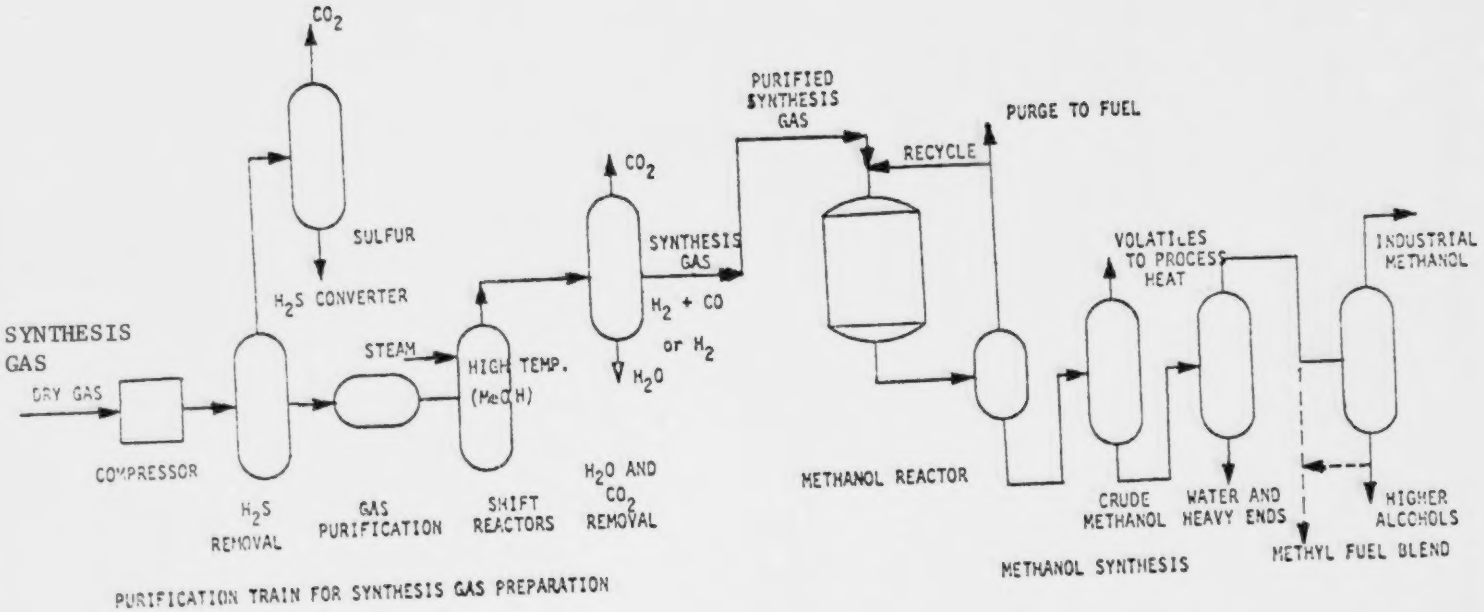

SYNTHESIS GAS
DRY GAS
COMPRESSOR
H_2S REMOVAL
CO_2
SULFUR
H_2S CONVERTER
GAS PURIFICATION
STEAM
HIGH TEMP. (MeOH)
SHIFT REACTORS
CO_2
SYNTHESIS GAS
H_2 + CO or H_2
H_2O
H_2O AND CO_2 REMOVAL
PURIFICATION TRAIN FOR SYNTHESIS GAS PREPARATION
PURIFIED SYNTHESIS GAS
RECYCLE
PURGE TO FUEL
METHANOL REACTOR
VOLATILES TO PROCESS HEAT
CRUDE METHANOL
WATER AND HEAVY ENDS
INDUSTRIAL METHANOL
HIGHER ALCOHOLS
METHYL FUEL BLEND
METHANOL SYNTHESIS

Figure 48. Low pressure methanol process (based on ICI process).(158)

very little published regarding intentional increases of by-product yield in methanol manufacture.

Ammonia Production--

Ammonia is not consumed as a fuel; in fact, the largest markets for ammonia are in the manufacture of fertilizers and explosives. However, natural gas fuel, which is in increasingly short supply, is used as the hydrogen source for the manufacture of ammonia.

$$N_2 + 3H_2 \rightarrow 2NH_3$$

The use of a gaseous substitute, derived from a biomass-to-energy conversion process, as a feedstock for ammonia production would contribute toward reducing the demand for natural gas. The synthesis gas, from either a pyrolysis or hydrogasification reaction, already contains some hydrogen and significant quantities of CO. The process for converting CO and H_2 synthesis gas to ammonia would be essentially the same as the process utilizing methane as the feed, with the exception of the reformer. This concept was examined by the city of Seattle in a study designed to determine the feasibility of converting municipal solid waste into ammonia.(159) The details of the process are well known and are not examined in detail in this study.

C_2-C_5 Hydrocarbons--

Battelle's Columbus Laboratories has developed a series of catalysts which convert synthesis gas to light hydrocarbons (C_2-C_5) in a Fischer-Tropsch process.(160) Synthesis of the light hydrocarbons can be represented by the following reactions.

$$(2n + 1)H_2 + nCO = C_nH_{n+2} + nH_2O$$

$$(n + 1)H_2 + 2nCO = C_nH_{2n+2} + nCO_2$$

Conversions between 21 to 55 percent per pass of carbon monoxide have been achieved. The hydrocarbon product formed has a composition similar to that listed in Table 66.

TABLE 66. LIGHT HYDROCARBON PRODUCT COMPOSITION

	Volume Percent
Ethane	23
Propane	9
Methane	68
Water	Trace
Total	100

The product gases can be used as a synthetic natural gas (SNG) which would have an increased heating value over normal methane. Separation of ethane from the product gases could yield a source of substitute petrochemical feedstock.

The process is in the laboratory development stage and represents a possible future use for synthesis gas produced from several processes such as pyrolysis or gasification.

Higher Hydrocarbons (Fischer-Tropsch Synthesis)--

The Fischer-Tropsch synthesis is basically the catalytic conversion of a mixture of carbon monoxide and hydrogen to a mixture of hydrocarbons and various oxygenated organic compounds. The nature and quantities of products are dependent on the catalysts and operating conditions used during the reaction.

The Fischer-Tropsch synthesis process was developed in Germany in the early twenties. Several large-scale plants were erected before the war and became a reliable source of fuel and chemical feedstocks. Several large plants were erected in Japan and demonstration plants were built in England and the U.S. A plant completed in Brownsville, Texas, in 1950 was designed to convert 2.5 million cubic meters per day (90,000,000 cubic ft/day) of natural gas to synthesis gas for the production of 326,000 metric tons per year (360,000 ton/yr) of gasoline and other liquid fuels, and 36,000 metric tons per year (40,000 ton/yr) of chemical products. Many technical difficulties were experienced, primarily in the synthesis sections, and economic considerations dictated shutdown decommissioning of the plant.(161)

The only operating plant at the present time is located at Sasolburg, South Africa, and has a capacity of 113,000 metric tons per year (125,000 ton/yr) of primary products. In the Fischer-Tropsch process as presently practiced at the Sasol-I plant, synthesis gas is produced from coal; the gas is purified to remove sulfur compounds which would poison the catalysts; and the mixture of carbon monoxide and hydrogen is fed into the catalytic reactors. The recovered products are separated by solvent extraction and fractional distillation techniques.

The most significant problem associated with large-scale operation is the method of dissipation of heat from the reactors to avoid inactivation of the catalyst. The heat is generated by the highly exothermic reactions. The optimum temperature ranges for nickel and cobalt catalysts are 170 to 205 C and 200 to 325 C for iron. Several methods and various designs of reaction vessels have been used to achieve this heat removal. Originally, water under pressure was used as the cooling medium. A fluidized-bed catalytic reactor is used at the Sasol plant. Experiments have been carried out with oil circulation, slurry, and hot-gas recycle.(162) The Sasol-I plant uses both the fixed-bed (iron-cobalt catalyst) Arge reactor and the fluidized-bed (promoted iron catalyst) M. W. Kellogg reactor. The product distributions for the two processes, as seen in Table 67, are quite different. A breakdown of the C_{5+} fractions are listed in Table 68.(163)

TABLE 67. PRODUCTS OBTAINED FROM KELLOGG AND ARGE UNITS OF SASOL-I PLANT(163)

Product	Distribution, percent Kellogg	 Arge
Methane	13.1	7.8
Ethylene	4.4	0.6
Ethane	5.8	2.6
Propylene	12.8	3.9
Propane	3.4	2.2
Butylene	10.0	2.5
Butanes	3.2	2.4
C_5 and above	39.0	75.7
Non-acid chemicals	7.3	2.3
Acids	1.0	--
TOTAL	100.0	100.0

TABLE 68. COMPOSITION OF THE C_{5+} FRACTIONS(163)

	Distribution, percent			
	Kellogg		Arge	
Product	C_5-C_{10}	C_{11}-C_{18}	C_5-C_{10}	C_{11}-C_{18}
Paraffins	13	15	45	55
Olefins	70	60	50	40
Aromatics	5	15	0	0
Alcohols	6	5	5	5
Carbonyl Compounds	6	5	Trace	Trace
TOTAL	100	100	100	100

A second plant, Sasol-II, was announced in 1974 and is scheduled to go onstream in 1979-1981. The Ralph M. Parsons Co. was awarded a three-year ERDA contract in 1974 which will include preliminary design work on a Fischer-Tropsch synthesis plant in connection with a coal-oil-gas refinery.

Liquid-Based Conversions

Methanol to Gasoline--

Methanol itself is a potential motor fuel or fuel additive that can be made from synthesis gas by existing technology. However, several problems are involved with using methanol directly as a fuel additive. A catalytic process has been demonstrated by Mobil Oil Corp. which converts methanol to hydrocarbons and water by the following reaction.

$$xCH_3OH \rightarrow (CH_2)_x + xH_2O$$

The hydrocarbons are predominantly in the gasoline boiling range (C_4 to C_{10}) with Research Octane Numbers of 90 to 100. The catalyst used in the reaction is a shape-selective zeolite. A typical product composition is illustrated in Figure 49.

About 75% of the products are in the C_{5+} fraction. Part of the n-butane fraction is included in the gasoline fraction, and C_3 and C_4 gases,, olefins, and isobutane can be converted by alkylation to increase the gasoline yield to 90% of the product (Figure 50). Currently, both fixed-bed and fluid-bed bench-scale reactors are operating. Mobil has a contract with ERDA (DOE) to design a pilot plant of 100 bbl per day capacity.(177)

Secondary Biochemical Processes

The Fermentation of Sugar Solutions to Ethanol--

Ethanol may be produced from any fermentable sugar by yeasts under suitable conditions. There are many available sources of fermentable sugars which can be classified into three areas.

(1) Saccharine materials - such as molasses, sugar cane, and fruit juices.
(2) Starch materials - such as grains, for example, oats, barley, rice, and wheat; and potatoes.
(3) Cellulosic materials - wood, waste sulfite liquor.

The operating conditions of the fermentation process and the product yields depend on the nature of the starting material and the microorganisms used in the process. The characteristics of a good yeast culture are (1) tolerance to high temperatures; (2) tolerance to high alcoholic, sugar, and non-sugar solids concentrations and (3) the ability to ferment rapidly.(164)

Process description of molasses fermentation--In the United States, molasses and grain are the principal raw materials used in ethanol fermentation. Strains of *Saccharomyces cerevisiae* are commonly used in molasses fermentation. Cultures are propagated in two stages: (1) small 150-ml flasks, and (2) 6-liter flasks which directly seed the initial fermentors.

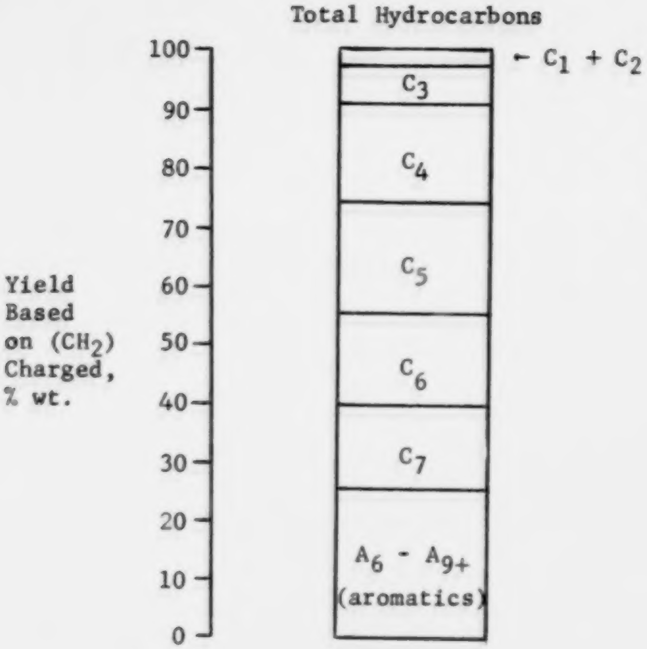


Figure 49. Product distribution from conversion of methanol.

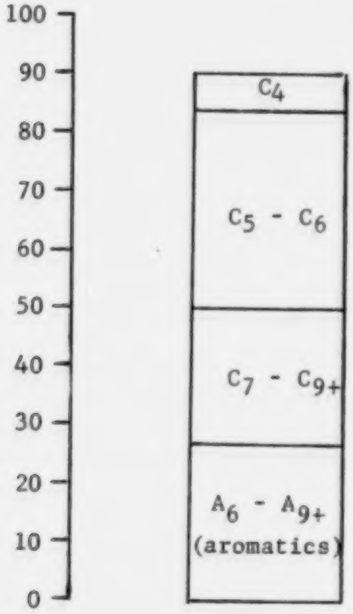


Figure 50. Gasoline fraction after alkylation.

The molasses is diluted with water to a sugar concentration of 14 to 18 percent and pumped to the fermentors. Inoculum which is 2 to 4 percent volume active yeast is added to the fermentor. The pH is adjusted between 4.0 and 5.0 with sulfuric acid. Small quantities of ammonium salts may be added to increase the rate and efficiency of fermentation.

Initial temperatures are usually between 21 and 27 C. Water sprays, internal cooling coils, or external coolers to remove heat formed by the exothermic reaction cool the mash during fermentation. Theoretically, 144 k-cal per kilogram of sugar (260 Btu/lb) are liberated during the following reaction.

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \text{(165)}$$

Government regulations allow four days for a cycle, but usually 36 to 50 hours are used for fermentation. The effluent from the fermentors is called a beer and is distilled in a beer still. The overhead vapors from the still which contain alcohol, waster, and aldehydes, are condensed and passed through a second column. Aldehydes are removed as overhead vapors and condensed. The effluent is pumped to a recycling column. Ninety-five percent alcohol is taken off the top of the column.

The higher boiling (90 to 150 C) fusel oils are removed further down the column and sold as impure amyl alcohol. The fraction is a mixture of isopropyl, isobutyl, isoamyl, and amyl alcohols. Water is discharged from the bottom of the rectifying column.

The principal waste stream in the process is the residue discharged from the bottom of the beer still. The stillage contains 7 to 10 percent solids and has a very high B.O.D. (18,000 to 22,000 ppm). A typical composition of stillage is listed in Table 69.

Residues from molasses fermentations have been used as animal feed and fertilizer. Another method of disposing of a portion of the stillage is to use it as a substance on which to grow yeast aerobically. The yeast is then mixed with molasses and fermentation proceeds anaerobically.(166)

The Melle process--In the fermentation of molasses, the conversion of sugar averages about 95 percent of the theoretical amount. Part of the remaining 5 percent is converted to cell mass and is, therefore, not available for alcohol fermentation. The Melle process is designed to partially reduce this loss by centrifuging out the yeast after fermentation and recycling the yeast to the next fermentor. The problem of bacterial contamination is avoided by washing the centrifuged yeast with large volumes of water and reducing the pH for several hours in the presence of CO_2.

The process has been applied in distilleries in foreign countries and in sulfite liquor plants in the U.S.(165)

Fermentation of wood sugar--Sugars produced from dilute acid hydrolysis are difficult to ferment by conventional methods. Wood-sugar fermentation was first carried out during World War I in the U.S. at plants in Georgetown,

TABLE 69. COMPOSITION OF STILLAGE(165)

Component	Wt. % (dry basis)
Mineral matter	28.5 - 29.0
Sugars	10.0 - 12.0
Proteins	8.0 - 10.
Volatile acids	1.0 - 2.0
Gums	20.0 - 22.0
Combined lactic acid	4.0 - 7.0
Other combined organic acids	1.0 - 2.0
Glycerol	5.0 - 6.0
Wax, phenolics, lignins, etc.	22.0 - 12.0

South Carolina, and Fullerton, Louisiana. The fermentations were started by adding wood-sugar to molasses and continued for 96 hours.

Toxic substances present in wood sugars are derived from four potential sources: (1) carbohydrate decomposition, (2) lignin decomposition; (3) extraneous materials present in wood; and (4) metal ions from corrosion of equipment. Operations which are successful in reducing the toxicity are: (1) steam distillation; (2) acclimation of yeast; (3) tin treatment; (4) adsorption; (5) pH adjustment; (6) high temperatures; and (7) sulfide precipitation. One advantage which exists in the fermentation of wood hydrolyzates is that they are so inhibitory there is virtually no problem with contamination.

A Springfield, Oregon, plant was designed to produce 40,500 liters (10,700 gal) of alcohol and to operate with continuous fermentations. Because the wood-sugar was not produced at full capacity nor at a steady rate, the plant was operated on a batch basis with recycling of the yeast. Some type of yeast recycling system is required in wood sugar fermentation to operate economically.

In this plant, the hydrolyzate was prepared for fermentation by neutralization with calcium hydroxide under 40 psi steam pressure. The neutralized liquor was filtered, cooled, and filtered a second time. Yeast was added immediately after the second filtration. The yeast used at the plant was Saccharomyces cerevisiae, although strains of Torulosis were also tested.

The maximum number of times for yeast recycle was not determined. The fermentation time for one percent yeast varied between 16 and 40 hours; most were complete in 24 hours. At the Springfield plant, 78 percent of the sugar was fermentable. The theoretical yield was 51.9 percent of alcohol and the actual yields varied between 44 and 48.5 percent. Thus, the fermentation efficiencies varied between 75 and 86 percent.(167)

The Anflow process--Union Carbide has developed an upflow packed column which acts as a continuous biological reactor. Several products could be produced from the fermentation process depending on the starting materials and microorganisms attached to the packing. Examples are (1) methane from sewage sludge; (2) lactic acid from whey; (3) methanol from sewage; and (4) ethanol from grains or other materials.

The process is in the laboratory experimental stage of development and the size of reactors varies between 1.5 inches in diameter and 2 feet in length to 5.5 inches in diameter and 5 feet in length. A simple schematic diagram of the reactor is given in Figure 51.

The greatest problem associated with the reactor is the difficulty in the attachment of microorganisms to the packing. However, flow-through rates are greatly increased compared to other fermentation processes.

In a large-scale unit, capital costs could be substantially reduced due to the decreased retention times and possible increased stability over conventional fermentation processes.(168,169,170,171,172)

The Fermentation of Sugar Solutions to Butanol/Acetone--

Pasteur was the first investigator to show butanol was a direct product of fermentation. During World War I, the demand for synthetic rubber and explosives stimulated the development of a commercial process for the fermentation of acetone. Butanol was formed as a by-product but later became the more desired end product when it was used in lacquers in the automotive industry. Fermentation plants were built in England, Canada, the U.S., and

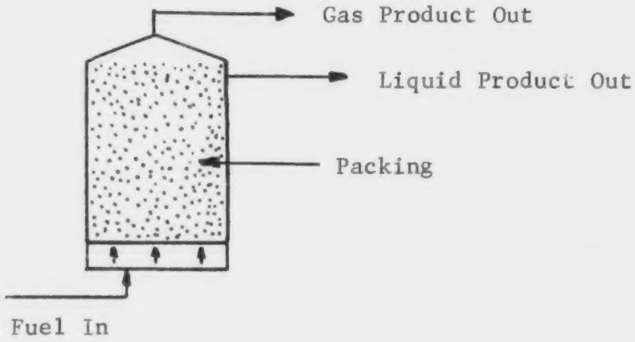


Figure 51. The Anflow reactor.

India. Butanol and acetone are now derived synthetically from petrochemicals because of the high costs of raw materials for fermentation.(173)

The microorganisms used in the fermentation process differ with the starting material. Clostridum acetobutylicum are used to ferment starches, and almost all species of the genus Clostridrium are used to ferment saccharin materials.

The optimum temperature for fermentation is 39.5 C (87 F). The initial pH is 5.5 to 6.5. The product yields based on 100 kg of raw material (blackstrap molasses) are listed in Table 70.(175)

The stillage has a solids content of 2.4 g per 100 ml and has a high concentration of riboflavin. The stillage can be distilled to a syrup which is evaporated and dried. The recovered material was used as a vitamin supplement for foodstuffs.(174)

Experiments were conducted in 1947 on the fermentation of wood sugars. It was found that sugar solutions produced under either very mild or very extreme conditions were difficult to ferment.(175)

The Fermentation of Sugar Solutions to Other Products--

The fermentation in which isopropanol and butanol are produced as end products are related to the butanol-acetone and ethanol-acetone fermentations. Several closely related organisms have the ability to produce isopropanol. Clostridium butylicum are the best known.

TABLE 70. MATERIAL BALANCE FOR ACETONE-BUTANOL FERMENTATION(175)

Starting materials	Kg
Total solids	81.5
Sugars	57.0
Protein	3.1
Ash	6.2
Yields	
Butanol	11.5
Acetone	4.9
Ethyl alcohol	0.5
Carbon dioxide	32.1
Hydrogen	0.8
Dry Feed	28.6

Several commercial plants were constructed in Formosa in 1943-44 which produced butanol, isopropanol, and acetone.

Raw materials used in the plants were sugar cane, sugar syrup, and blackstrap molasses. The final product composition varied with the nature of the raw materials and operating conditions during fermentation. The products were formed in the ranges of 53 to 65 percent butanol, 19 to 44 percent isopropanol, and 1 to 24 percent actone. The products were separated by continuous distillation.

Wood sugars were investigated by Sjolasder, Langlykke, and Peterson in 1938 as a source of butanol and isopropanol. The wood hydrolyzates were treated with calcium carbonate to increase the pH, filtered, treated with lime to precipitate iron and copper, and filtered a second time. As a result, more isopropanol was produced from wood sugars than from glucose. A second experiment showed the increased isopropanol production was due to the acetic acid present in the solution.(176)

PRODUCT STORAGE AND TRANSPORTATION

The objective of the technologies reviewed in this report is to produce fuels of commercial significance. A review of the products involved will reveal that many are commercial commodities already utilized in utility, fuels, or chemical industries. Because this is the case, good engineering practice has been developed for most and need not be reviewed in detail in this report. There are several good reference handbooks available which give excellent perspective to the range of considerations needed in design.(178,179, 180)

The purpose of this section of the report, then, is to briefly highlight special functional requirements. It is particularly important to do this in the context of the likely environments where the technologies will be implemented (for example, rural agricultural communities and municipal waste handling facilities), and to flag those areas which should be investigated in more detail in later work.

Direct Conversion Systems

The major product from these systems will be steam and/or electricity. Storage of these products at the current level of technological development, for more than transient periods, is economically impractical. Consequently, the major consideration is distribution.

Electrical power distribution equipment is dangerous for untrained staff, but the common fare of electric utility companies. Likewise, many municipalities have departments dedicated to power production. Since any electrical production facility will likely involve a utility as the customer, it would seem logical to use their expertise at and beyond the point of electricity production.

Steam distribution is well established, and competent designs are well within the capabilities of most architect and engineering firms. The major hazard is high temperature, a hazard familiar to essentially all commercial establishments.

Pyrolysis Systems

These systems may produce gases, liquids, or chars. Gaseous systems will generally produce low to medium Btu product streams, which are unlikely to be stored for long periods. It is probable in some situations that the gas will be combusted or chemically converted at sites located several miles from the production facility. Two components in the typical product gases need to receive special consideration: hydrogen and carbon monoxide.

Even without the presence of hydrogen, the gas should be regarded with caution due to its explosive and asphyxiation qualities. The presence of hydrogen, a highly explosive and inherently diffusive agent, serves to reinforce the need for transport by tank car. This will likely require use of special code enclosures for electrical connections and equipment in some instances, and careful monitoring of all piping connection, most importantly where high pressure transmission of the gases are involved. High pressure hydrogen leaks have reportedly self-ignited in some instances and could constitute fire and possibly explosive hazards.

Carbon monoxide is, of course, a highly toxic agent. However, housekeeping practices established for hydrogen, as noted above, should minimize the likelihood of escape.

Liquid streams produced in pyrolysis systems are expected to have roughly comparable characteristics with their petroleum counterparts. Spills and leakage will have to be controlled to the same level as required for the petroleum and petrochemical industry. Human exposure limitations are expected to be similar to hydrocarbons with approximately the same characteristics, but this is a speculation and needs to be confirmed.

Storage equipment is likely to be similar to that used for petroleum products, except for the noted tendency of these liquids to "polymerize" and become more viscous. Heating and agitation may be required. However, heating reportedly increases polymerization rates. If suitable inhibitors can be found, then long-term storage may not be a significant problem; if not, only short-term storage may be possible.

Char storage does not present any new technological problem. It is possible that some chars may spontaneously combust, as will coal under certain conditions. Also, care will have to be taken to collect and treat run-off from open storage piles, as these may contain appreciable concentrations of toxic substances, notably heavy metals.

Hydrogenation Systems

The products and associated problems with these systems are expected to be categorically similar to those noted in the previous section.

Acid Hydrolysis Systems

The product from this system will be a sugar-rich aqueous stream. In most instances, this will likely be converted on-site to secondary products, probably ethanol.

Storage does not represent substantial problems as it is well established in the current sugar industry, as well as in earlier plant practice (see the report section on Acid Hydrolysis). One consideration which may be important, especially for long-term storage, is prevention of microbiological contamination. Contamination could cause two types of problems. Obviously, inadvertent culturing of some glucose-using microorganisms could result in loss of product in storage. Equally as important, unnoticed contamination could create downstream process problems in subsequent fermentation steps.

Anaerobic Digestion Systems

The handling and storage of methane, the major product of this technology, is well established in the natural gas industry. On-site storage of significant quantities of this product is unlikely, because of unfavorable density characteristics.

However, compression and transmission to a main natural gas trunk pipeline is anticipated to be required in most installations. Since transmission pressures are often 1000 psig, or greater, care will have to be exercised in operating this equipment. Thorough training of operating staff in the safety features associated with these functions will be necessary.

Enzymatic Hydrolysis Systems

The same considerations noted under the section on acid hydrolysis systems hold here as well. However, because this conversion process is not likely to sterilize the product, contamination potential will be increased substantially, and storage time requirement may need to be more restrictive.

Methanol Production Systems

These systems will require special consideration. While there is considerable established practice in the chemical industry for handling methanol, use of this highly toxic material in fuel distribution systems will present a host of new problems. Control of spills will be essential. Spills and pipeline leakage in transport could adversely affect both humans and animals in contact, as well as crop lands. In an agricultural setting, this may be particularly significant to conventional heterogeneous farming systems. The tendency of methanol and methanol mixtures to pick up water may adversely affect product quality and require special storage constraints. The health and safety implications of methanol storage and distribution needs to be studied thoroughly, before large-scale implementation of the technology is undertaken.

These comments hold for methyl fuel products as well.

Light and Mid-range Hydrocarbons

Storage and transportation of these products are common practice in the petroleum and petrochemical industry. While safety and health requirements are extensive, they are well established.

Ethanol Fermentation System

Storage and transportation of the industrial ethanol are also well known in the chemical industry. Design of storage and transportation equipment does not represent technological difficulties; however, IRS regulation relative to production and distribution of ethanol must be considered. While there is not the degree of concern as with spills, it is conceivable that continued exposure of personnel in enclosed spaces might adversely affect operative decision making.

Other Fermentation Systems

The comments noted above generally hold for other fermentation products as well.

DEVELOPMENT OF REGIONAL SCENARIOS OF BIOMASS CONVERSION PLOTS

Introduction

The previous sections have been directed at characterizing the individual biomass sources and energy conversion technologies. The applicability of any of the conversion technologies, however, for transforming biomass waste into a usable form of energy for a particular region depends upon two major factors: (1) the availability of suitable quantities of biomass feedstock for a reasonable size conversion facility, and (2) the applicability of the conversion process to the specific type of biomass feedstock and the marketability of the conversion product in that region.

The resultant regional environmental impact of such a system must address the implications of an integrated biomass production/collection and conversion system in total and will understandably vary with different regions and conversion technologies. To this end, a series of six scenarios have been prepared to superficially examine the environmental implications of different conversion technologies applicable to different geographical areas of the United States. The engineering and environmental analyses of each region are not comprehensive in nature as such developments are beyond the scope of this report. The analyses are, however, sufficiently detailed to identify generically the environmental and social consequences of such ventures.

Rationale for Scenario Source/ Conversion Process Selection

Characteristically, the availability of most biomass sources is highly regionalized. Likewise, a review of the chemical and physical properties of the materials shows that there exists inherent characteristics which make individual biomass sources more amenable to one broad classification of conversion process, in contrast to a second class. Consequently, the strategy was adopted that regional sources and their "natural" conversion process counterparts would be utilized wherever possible. Over this criteria was superimposed the necessity of trying to depict most of the relevant conversion technology, as well as a specialized scenario directed at development of a mobile facility.

Consideration of region selection was limited to the continental United States. Likewise, broad areas of the western region which are particularly arid were excluded from serious consideration because their development would imply importation of tremendous quantities of fresh water, a project of such monumental environmental significance that it would overwhelm any factors related to the various source/conversion process development. While consideration of such an undertaking is not beyond consideration from the context of biomass source development, dealing with it in a competent fashion is beyond the scope of this study.

Four regions, only partially homogeneous in nature, were defined for use in this study. These were the Northeastern, Southern, Midwestern, and West Coast regions. The states included in these regions are listed in Table 71 and shown graphically in Figure 52. Review of these regions will show that the definition adopted here will not correspond to normal geopolitical classification. Likewise, the distinction between regions is necessarily arbitrary in some cases because change from the characteristics of one region are continuous rather than abrupt events.

The Northeastern region consists of the New England and upper eastern seaboard states down to Virginia. These states are highly populated; large forest tracts exist in portions of New England as well as several other states. Some agriculture exists, but tonnage quantities are much smaller than other regions. An ocean coastline as well as prodigious quantities of fresh water exist. However, the climate is temperate so that mariculture yield would be lower than in southern and western regions. Likewise, major ports and the commensurate commercial traffic also tend to mitigate against development of ocean-based aquatic systems. While the freshwater systems are large, their dedication to industrial use makes fresh water aquaculture unlikely, as does the high cost of land. Energy farming crops are obviously of only passing consideration.

Consequently, the major biomass sources of interest in this region are urban waste, silviculture, and forest residue. Since these materials all have fairly low moisture content and relative high net Btu content, a thermochemical conversion system in the region appears to be indicated.

The Southern region is characterized as highly productive of biomass. The warmer climate generally extends growing seasons and increases annual yields. Energy-farming crops (sugar cane, various grasses) may become attractive in this region, as might silviculture. The existing commitment to pulp and forest products tends to reinforce this latter biomass category, but this industry's existence also represents a highly competitive use for

TABLE 71. STATES CONTAINED IN VARIOUS REGIONS DEFINED FOR STUDY

Northeast Region

Connecticut
Delaware
Maine
Maryland
Massachusetts
New Hampshire
New Jersey
New York
Pennsylvania
Rhode Island
Vermont
Virginia
West Virginia

Southern Region

Alabama
Arkansas
Florida
Georgia
Louisiana
Mississippi
North Carolina
South Carolina
Tennessee
Texas (partial)

Midwest Region

Illinois
Indiana
Iowa
Kansas
Kentucky
Michigan
Minnesota
Missouri
Montana (partial)
Nebraska
North Dakota
Ohio
Oklahoma
South Dakota
Texas (partial)
Wisconsin
Wyoming (partial)

West Coast Region

California
Oregon
Washington

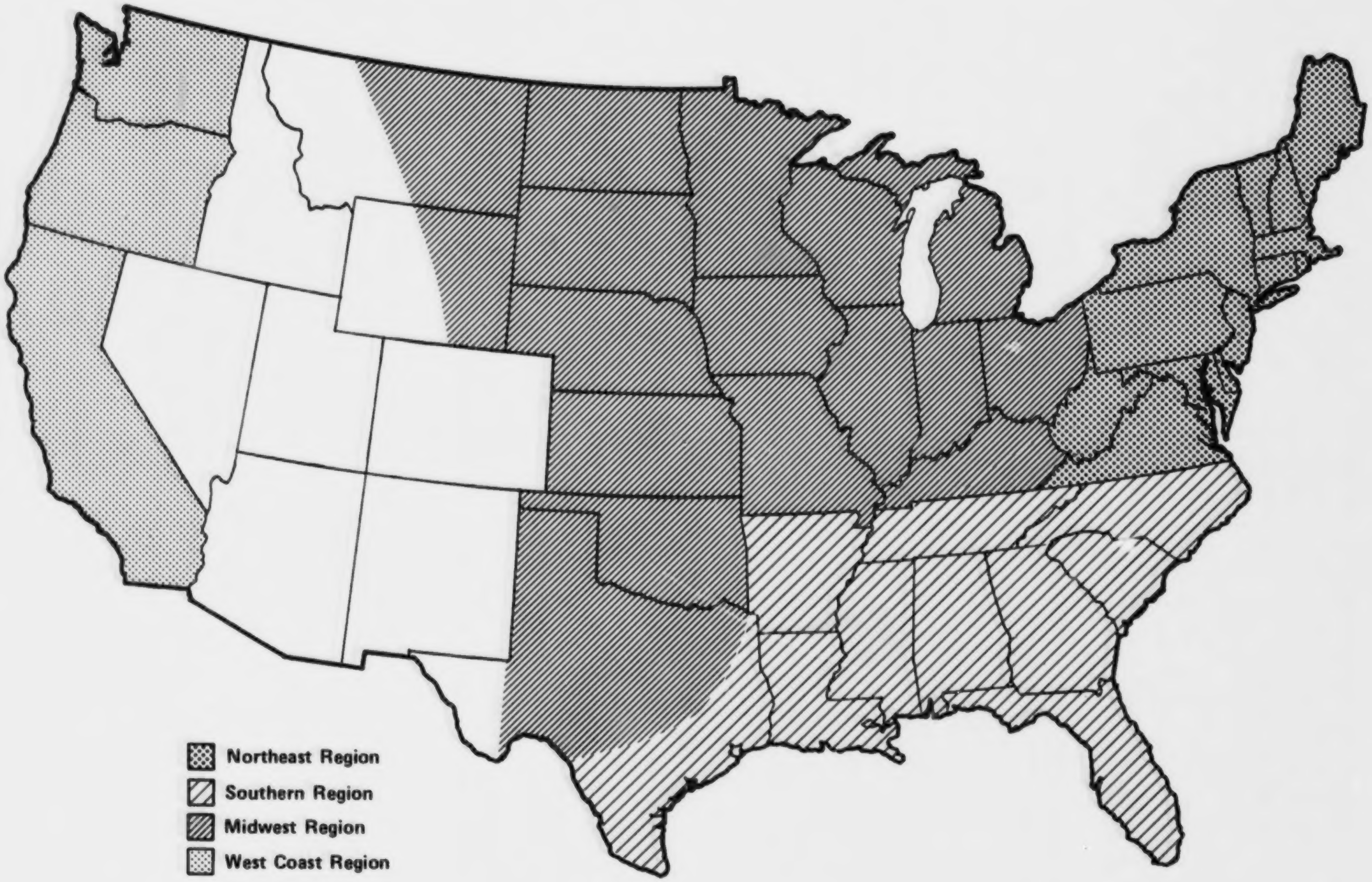

Northeast Region
Southern Region
Midwest Region
West Coast Region

Figure 52. Pictorial presentation of regions.

the resource. Agriculture production exists at appreciable levels, but not nearly on a scale with the Midwestern region. Likewise, animal husbandry is widespread with especially high concentrations in Florida. However, absolute totals are dwarfed by Midwestern concentrations. An extensive coastline along with semi-tropical weather conditions would appear to make aquaculture a viable option, and kelp production has been proposed. The lack of specific experiments related to this thesis as well as the danger from hurricanes in the region tend to balance their positive attributes. Urban population is relatively sparse, especially in comparison to portions in the Midwest, the East and West.

These considerations, especially the generally high productivity of the region, have been the basis for choosing a multiple feedstock plant. The plant will be based on cellulose conversion and will process a combination of silviculture (slash pine) or an energy crop residue (bagasse) as feedstock.

The Midwestern region is the largest in terms of area and is the region most highly dedicated to high-volume agriculture. Obviously, agricultural residue including both crop and animal wastes are available in large quantities. Some forestry exists, especially along boundaries with other regions. Large urban centers are distributed throughout the region so that urban and industrial waste inventories are substantial. Marine agriculture is, of course, out of the question. However, fresh water systems, especially in the Great Lakes section, remain a possibility. Tropical energy crops (e.g., sugar cane) are possible only in very limited sections; however, grasses would appear viable, although their use would no doubt be limited to marginal lands.

One special consideration is the existence of much of the U.S. coal reserves in the region. This is of interest because strip-mined lands are excellent candidates for combined reclamation/energy production. Both grasses and certain tree species are candidates.

Two scenarios have been defined for this region. One is based on combined crop and manure wastes and the other on silviculture products grown on strip-mined lands.

The final region is that of the West Coast. This region is characterized by some of the most productive land in the United States. It is also some of the most expensive land, and its commitment is almost totally for direct human consumption. Consequently, its use for energy crops would appear unlikely.

Several large urban population centers exist in the region, as does a very significant forest products industry. The coast is a natural site for kelp, the major aquaculture crop presently being considered. Fresh water is limited; however, wastewater from metropolitan centers could conceivably be the source of a fresh water aquatic crop.

Given this diversity of potential feedstocks, the choice of feedstocks for the two scenarios in the West Coast region is reduced to accommodating choices not previously made. Primarily for this reason, a scenario based on urban waste and one on combined kelp and urban waste were chosen.

Finally, the special case of a mobile conversion plant, with multiple feedstock capabilities, was considered in order to provide insight into the other end of the process plant size spectrum.

Process Selection for Region-Based Feedstock

In this section, biomass waste-to-energy conversion systems were selected and examined in each of the four regions. The intention was, where possible, to match the characteristics of energy needs with the resources and appropriate conversion processes for the region. For example, the scenario developed for the Northeast, where there is an abundance of relatively dry urban and forest wastes, is to produce material, which might be used as a supplemental automobile fuel and for peaking electrical power. An attempt was made in the selection of the conversion processes to include representative processes from both the thermochemical and biochemical areas.

The criteria used in the selection of each process included not only the state of development of the process but (1) the applicability of the process to the specific biomass feed as dictated by the physical characteristics of the feed and the operational constraints that the feeds impose on the process, and (2) the marketability of the energy or conversion product in the specific region.

For each region, the physical characteristics, the methods of harvesting, the seasonal influences, and the geographical distribution of the waste feedstock were examined. Within these constraints, a reasonable determination of the plant capacity was made and an appropriate plant site selected. A brief description was developed for each selected process along with a generalized process flow schematic, a material balance, and estimates of the size of the major process equipment were also prepared.[a] A summary of the salient features of each of the processes for the six scenarios is presented in Table 72.

Scenario No. 1 (Northeast)--

In this six-state region (Maine, New Hampshire, Vermont, Connecticut, Massachusetts, and Rhode Island), approximately 10.4 million metric tons of forest residue is made available each year from logging operations. The heaviest concentration of forest residue lies in the three-state region of Maine, Vermont, and New Hampshire where 8.4 million metric tons are discarded annually. It is in this region that a waste-to-energy conversion plant would be most appropriately located.

Several energy conversion processes are applicable for treating the forest wastes, direct-fired boiler feed, hydrolysis with fermentation to ethanol, pyrolysis to a fuel gas with subsequent combustion, or pyrolysis to a synthesis gas for the manufacture of a fuel substitute, e.g., methane or methanol. Of these processes, direct boiler feed is the most commonly employed

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(a) The material balances should not be construed as being rigorous determination as sufficient experimental or analytical data were usually not available and conversion factors and yields were based solely on engineering judgment.

TABLE 72. SUMMARY OF WASTE TO ENERGY PROCESSES FOR THE SIX SCENARIOS

Scenario	Type of Waste	Type of Process	Size of Process (metric tons/day)	Product Produced
No. 1 (Northeast - Maine, New Hampshire and Vermont)	Forest residue	Pyrolysis followed by methanol production	5,000	Methyl fuel
No. 2 (South - Louisiana)	33% bagasse, 67% pine slash	Acid hydrolysis with fermentation	3,000	95% ethanol
No. 3 (West Coast)	50% kelp 50% urban refuse	Anaerobic digestion, 2-stage	10,000	SNG
No. 4 (Midwest - Ohio)	80% European alder, 20% corn residue	Gas turbine electric generator	350	Electricity
No. 5 (Midwest - Kansas)	4% feedlot waste 96% wheat straw	Anaerobic digestion, 1-stage	10,000	SNG
No. 6 (West Coast Urban Center)	Urban refuse	Direct boiler feed	5,000	Low pressure steam

Scenario	Quantity of Product Produced (metric tons/day)	Product Uses	Waste Streams	Major Pollutants
No. 1 (Northeast - Maine, New Hampshire and Vermont)	790	Automobile and boiler fuel	Pyrolyzer ash, condensed water	High COD in condensed water
No. 2 (South - Louisiana)	204	Petrochemical feedstock	Calcium sulfate sludge, still and rectifying bottoms	Sulfate, high BOD
No. 3 (West Coast)	705	Utility gas	Digester sludge, brine off gas brine liquid waste	High BOD
No. 4 (Midwest - Ohio)	16.5 mw (per 8 hour day)	Electrical peaking power	Bottom ash and flue gas	--
No. 5 (Midwest - Kansas)	1.73×10^6 m^3/day	Utility gas	Column bottoms digester sludge	High BOD
No. 6 (West Coast Urban Center)	16,800	Industrial steam or municipal heating & cooling	Bottom ash and flue gas	--

wood waste-to-energy conversion process, and wood-fueled boilers are commercially available in a wide range of sizes. The process, however, has limited application and is site-specific, i.e., the generated steam must be consumed on-site rather than in the energy-intensive urban centers of the East.

Hydrolysis of wood waste has been technologically demonstrated on a commercial scale and is regarded as a viable candidate process. The hydrolysis reaction is conducted in a water medium, however, and the relatively low moisture content of the forest residues, as opposed to the residue wastes in other regions suggests that a combustion or pyrolytic thermal conversion process, rather than a water-intensive hydrolysis process, would more effectively capitalize on the physical characteristics of the raw forest waste.

The pyrolysis of the wood waste to produce a fuel gas suffers from the site-specific constraints characteristic with the direct boiler feed process. The fuel gas cannot be stored and would not be suitable for incorporation into the natural gas distribution network.

A pyrolysis process with conversion to a secondary fuel would permit the fuel to be utilized in regions not in close proximity to the pyrolysis plant. Some of the secondary fuels that could be manufactured from the pyrolysis synthesis gas are methane, C_2-C_5 hydrocarbons, and methanol (or methyl fuel). Of these, methanol was selected as the most appropriate fuel for the Northeast region due to its versatility, applicability as an automobile fuel substitute, and the ease with which it can be transported and stored.

Of the dozen or so existing pyrolysis processes, the Union Carbide Purox Process was regarded as the most suitable choice for producing a synthesis gas from the wood waste. The process has been demonstrated on a commercial scale and produces a gas high in H_2 and CO with little nitrogen or inert impurities. Of the two major methanol production process schemes, low pressure and high pressure, the low pressure process was chosen because of its characteristically lower capital cost and milder operating conditions. A detailed explanation of the rationale for these two selections is presented in a draft Battelle report to the Environmental Protection Agency on methanol production from non-coal sources.(181)

Process description--Some of the salient features of the feedstock and the conversion process are presented in Table 73. Figures 53 and 54(158) are schematic flow diagrams of the pyrolysis and methanol processes and Table 74 presents a material balance of the overall process.

The pyrolysis facility will consist of a single 1000-ton-per-day oxygen-generating plant, sixteen 315-metric-ton-per-day pyrolysis reactors (4 meters in diameter by 13 meters high), a gas cleanup module, and a 2500-cubic-meter-per-day wastewater treatment plant. Raw wood chips will be fed from the storage pile via conveyor belt into the individual feed hoppers (Stream No. 1). A ram feeder will introduce the wood fed into the top of the reactor where hot combustion gases, rising up through the wood chips, will dry and pyrolyze the wood to a gaseous product. Pure oxygen (Stream No. 2), fed into the combustion zone, will provide the environment for combustion of the wood. Approxi-

TABLE 73. SUMMARY OF FOREST RESIDUE TO METHYL FUEL PROCESS

(Northeast Region)

Waste Feedstock

Characteristics of Waste:

Type of waste - forest residue (tops of trunks, branches, and stumps)

Moisture content - 45 percent

Ash content - 3 percent

Heating value - 2600 kcal/kg (4675 Btu/lb)

Bulk density (green) - 800 kg/cu. m. (54 lb/cu. ft.)

Method of Harvesting Waste:

The forest residue from logging operations or from stand improvement and thinning operations will be collected on site, chipped, loaded into a truck and transported to the centrally located energy conversion plant.

Geographic Aspects of Waste:

Location of waste sources - the forest residues will be harvested from the commerical forest regions of Maine, Vermont and New Hampshire.

Geographical density of waste - based on a total, for the three state region, of 8.4×10^6 metric tons per year of sustained harvest of forest residue and, 16.9, 5.0 and 4.4 million acres of commercial forest residue is estimated to be 0.32 metric tons per acre per year. Based on the total area of three states, and the fraction of area devoted to commerical forestry (80 percent), the overall effective harvestable yield is approximately 0.26 metric tons per acre per year.

Energy Conversion Plant

Type of Plant:

Purox pyrolysis followed by a low pressure methanol or methyl fuel process

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TABLE 73. (continued)

Product:

Methanol or methyl fuel

Size:

5000 metric tons per day (chipped forest residue)

Geographical Location:

Centrally located in the three state region, preferably near the Maine-New Hampshire border.

Based on a 90 percent plant load factor and an effective harvestable forest waste density of 0.26 metric tons/acre, sufficient feedstock should be available, on a continuous year-round basis, within a radius of 55 miles from the central plant.

Storage Facilities:

Area will be provided for 7 days of open storage. The volume occupied by the 35,000 metric tons of wood chips is approximately 41,000 cu. m. (1.4 million cu. ft.). This volume would constitute a mound approximately 5 meters high by 90 meters on a side (15 ft. high by 300 ft on a side).

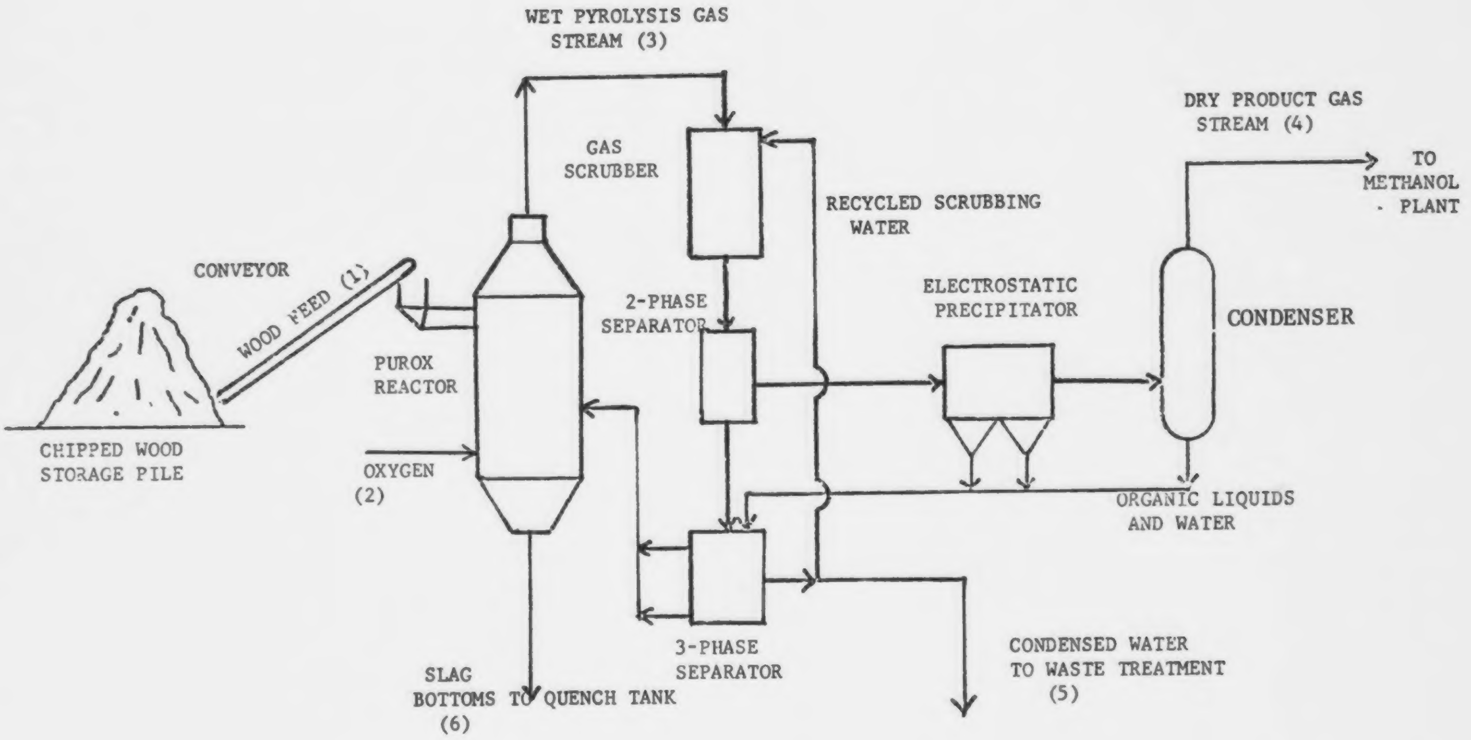
WET PYROLYSIS GAS STREAM (3)
GAS SCRUBBER
RECYCLED SCRUBBING WATER
DRY PRODUCT GAS STREAM (4)
TO METHANOL PLANT
CONVEYOR
WOOD FEED (1)
2-PHASE SEPARATOR
ELECTROSTATIC PRECIPITATOR
CONDENSER
PUROX REACTOR
CHIPPED WOOD STORAGE PILE
OXYGEN (2)
ORGANIC LIQUIDS AND WATER
3-PHASE SEPARATOR
CONDENSED WATER TO WASTE TREATMENT (5)
SLAG BOTTOMS TO QUENCH TANK (6)

Figure 53. Process flow schematic of wood waste pyrolysis system.

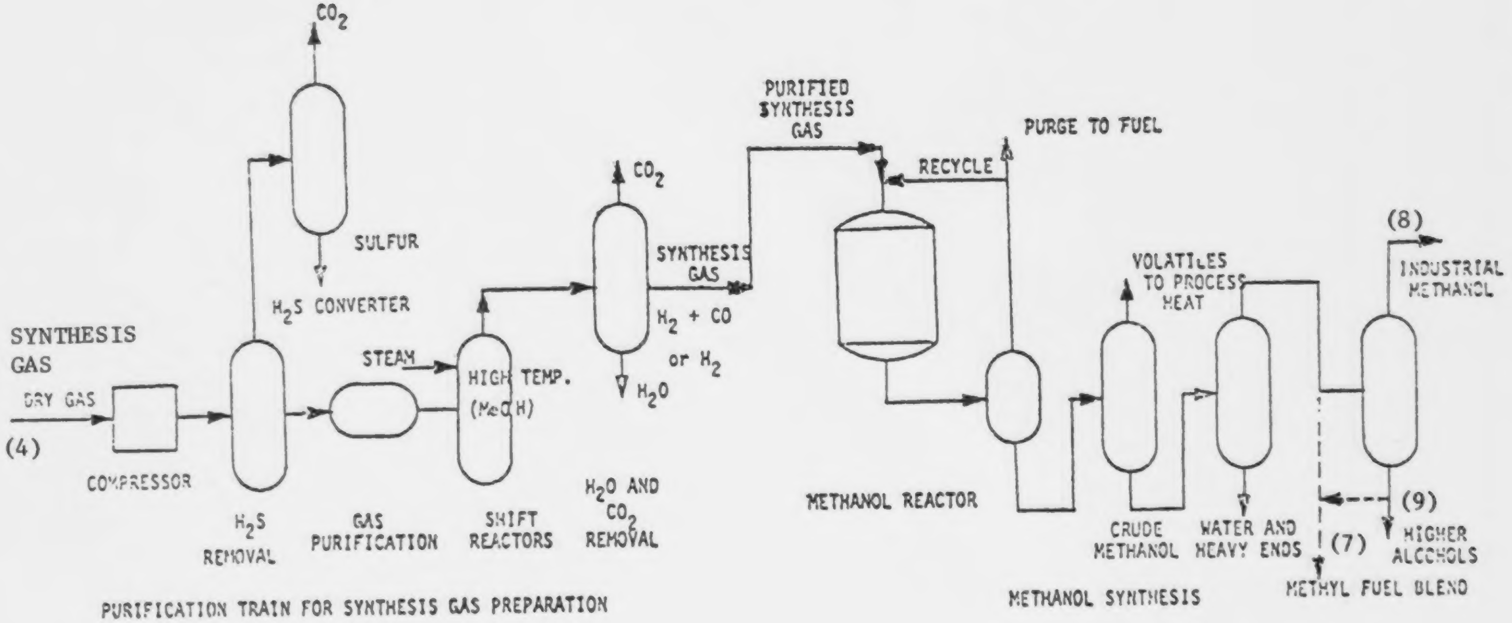
SYNTHESIS GAS
DRY GAS
(4)
COMPRESSOR
CO_2
SULFUR
H_2S CONVERTER
H_2S REMOVAL
STEAM
GAS PURIFICATION
HIGH TEMP. (MeOH)
SHIFT REACTORS
CO_2
SYNTHESIS GAS
$H_2 + CO$ or H_2
H_2O
H_2O AND CO_2 REMOVAL
PURIFIED SYNTHESIS GAS
RECYCLE
PURGE TO FUEL
METHANOL REACTOR
VOLATILES TO PROCESS HEAT
CRUDE METHANOL
WATER AND HEAVY ENDS
(8)
INDUSTRIAL METHANOL
(9)
HIGHER ALCOHOLS
(7)
METHYL FUEL BLEND
METHANOL SYNTHESIS
PURIFICATION TRAIN FOR SYNTHESIS GAS PREPARATION

Figure 54. Low pressure methanol process based on ICI process.(158)

TABLE 74. MATERIAL BALANCE FOR WOOD WASTE PYROLYSIS PROCESS

Basis: 5000 metric tons of chipped wood waste

Stream	Weight Percent	Metric Ton
Stream (1) Chipped Wood Waste		
Organic cellulosic compounds	51.7	2585
Water	45.0	2250
Ash	3.0	150
Sulfur	0.1	5
Nitrogen	0.2	10
Total	100.0	5000
Stream (2) Oxygen		
Assumed pure		1000
Stream (3) Wet Gas	Volume Percent	
H_2	11.15	59
CO	19.1	1320
CO_2	11.9	1390
CH_4	2.7	112
C_2H_4	1.5	72
H_2S	0.02	1
N_2	0.08	1
H_2O	53.5	2600
Oils	--	250
Other water solubles	--	50
Total	100.0	5855
Stream (4) Dry Gas		
H_2	22.3	59
CO	38.2	1320
CO_2	23.9	1390
CH_4	5.4	112
C_2H_4	3.0	72
H_2S	0.04	1
N_2	0.16	1
H_2O	7.0	170
Total	100.0	3125

TABLE 74. (continued)

Stream	Weight Percent	Metric Ton
Stream (5) Condensed Water		
Water	98.0	2430
Other water solubles	2.0	50
Total	100.0	2480
Stream (6) Slag		
Predominantly Ash		145
Stream (7) Methyl Fuel Blend		
Methanol	94.0	742
High alcohols	2.0	16
Water	4.0	32
Total	100.0	790
Stream (8) Purified Methanol		
Methanol	99.9	738
Higher alcohols	0.1	1
Total	100.0	739
Stream (9) Higher Alcohols		
Methanol	8.0	4
Higher alcohols	30.0	15
Water	64.0	32
Total	102.0	51

mately 230 standard cubic meters (9200 scf) of pyrolysis gas (Stream No. 3) will exit each reactor per minute. The gas will be manifolded into a common line and pass through a gas cleanup system consisting of a wet scrubber, an electrostatic precipitator, and a condenser. Approximately 3120 metric tons per day (3530) tpd) of the dry synthesis gas (Stream No. 4) will be produced.

The product synthesis gas, with a composition typical of that shown in Table 74, will be directed to the methanol facility where it will be compressed to about 50 atm. and passed through an absorption sequence for the removal of H_2S and other sulfur compounds. The gas will then be sent to a series of guard chambers which hydrogenate the unsaturated compounds and remove any remaining traces of H_2S and chlorine compounds. This sequence of guard chambers protects the water-shift and methanol catalyst from contamination.

The next step, the water-gas shift reactor will employ an iron oxide-chromium oxide type catalyst to convert the carbon monoxide and steam to carbon dioxide and hydrogen. The objective is to adjust the hydrogen to carbon monoxide ratio to that desired for the methanol synthesis. The normal temperature range for this reaction is 380-510 C (650-850 F).

Following the water-gas shift reaction, another absorbing train will remove excess CO_2 to reduce the load on the methanol reactor and other downstream equipment. The purified gas will enter the methanol reactor where, at 50 atm and 250 C (480 F), the carbon monoxide and hydrogen will react over a catalyst to form methanol. The product will be subsequently purified in a devolatilization column and dewatering column and distilled to separate it from the higher alcohols. For use strictly as a fuel, the higher heating value of the heavier alcohols would augment the combustion characteristics of the product alcohol and the final distillation step could be eliminated in favor of forming a methyl fuel blend (Stream No. 7). From the 5,000 metric tons per day of forest residue feed, approximately 790 metric tons of methyl fuel or 739 metric tons of purified methanol (Stream No. 8) and 51 metric tons of heavier alcohols (Stream No. 9) would be produced per day.

Environmental aspects--In the pyrolysis process, approximately 150 metric tons per day of wood ash (Stream No. 6) will be withdrawn as slag from the reactor bottom. The slag will be quenched, separated from the water, and transported to a landfill for disposal. An analysis of ash residue obtained from the burning of various types of wood bark is presented in Table 75 and an analysis of boiler ash from an approximately 70 percent bark-30 percent wood fuel burned in a Eugene, Oregon, power plant is presented in Table 76. As expected, the major components are inert silicon (silica) and aluminum (alumina) oxides). Because of the similarities of the elemental analysis of wood, regardless of species or location (as noted in Table 75), the ash composition from wood combusted in Vermont or Maine should be similar to the analysis in Tables 75 and 76. The wood ash can be generically characterized as a relative inert powdery solid with a minor fraction of sodium, magnesium, and potassium along with the trace amounts of heavy metals.

Approximately 2500 cubic meters per day (670,000 gpd) of water and water solubles (Stream No. 5) will be condensed from the product gas. The water will be high in BOD and COD and will require secondary treatment prior to

TABLE 75. CHEMICAL ANALYSIS OF BARK AND BARK ASH(182)

Analyses (dry basis), % by wt	Pine	Oak	Spruce	Redwood
Proximate				
Volatile matter	72.9	76.0	69.6	72.6
Fixed carbon	24.2	18.7	26.6	27.0
Ash	2.9	5.3	3.8	0.4
Ultimate				
Hydrogen	5.6	5.4	5.7	5.1
Carbon	53.4	49.7	51.8	51.9
Sulfur	0.1	0.1	0.1	0.1
Nitrogen	0.1	0.2	0.2	0.1
Oxygen	37.9	39.3	38.4	42.4
Ash	2.9	5.3	3.8	0.4
Heating value, Btu/lb	9030	8370	8740	8350
Ash Analyses, % by wt				
SiO_2	39.0	11.1	32.0	14.3
Fe_2O_3	3.0	3.3	6.4	3.5
TiO_2	0.2	0.1	0.8	0.3
Al_2O_3	14.0	0.1	11.0	4.0
Mn_3O_4	Trace	Trace	1.5	0.1
CaO	25.5	64.5	25.3	6.0
MgO	6.5	1.2	4.1	6.6
Na_2O	1.3	8.9	8.0	18.0
K_2O	6.0	0.2	2.4	10.6
SO_3	0.3	2.0	2.1	7.4
Cl	Trace	Trace	Trace	18.4

TABLE 76. SPECTROGRAPHIC ANALYSIS OF HOGGED FUEL ASH(182)

Components	Concentration, percent
Silicon (Si)	19.6
Aluminum (Al)	3.6
Calcium (Ca)	2.9
Sodium (Na)	2.1
Magnesium (Mg)	0.8
Potassium (K)	0.3
Titanium (Ti)	0.1
Manganese (Mn)	0.016
Zirconium (Zr)	0.006
Lead (Pb)	0.003
Barium (Ba)	0.010
Strontium (Sr)	0.002
Boron (B)	0.003
Chromium (Cr)	Less than 0.001
Vanadium (V)	Less than 0.001
Copper (Cu)	Less than 0.001
Nickel (Ni)	Less than 0.001
Mercury (Hg)	Nil
Radioactivity	Nil

discharging into a sewage system. All oils and particulates collected in the gas cleanup system will be combined and recycled to the reactor.

The discharge streams from the methanol process are (1) the purge stream following the methanol reactor controlling the buildup of hydrocarbon compounds, particularly methane and ethane, (2) the condensed water from the shift reactor, (3) the effluent from the methanol devolatilizing column, and (4) the bottoms from the dewatering column; these streams are described in more detail below. The H_2S stripped from the absorber in the stripping column does not pose an environmental threat as it would be directed to a Claus plant for conversion to elemental sulfur.

The hydrocarbon purge stream regulates the quantity of methane and ethane that builds up in the methanol recycle stream. Due to the relatively high concentration of methane and ethane in the pyrolysis synthesis gas, the purge gas constitutes a significant volume, about 4 percent of the raw waste feed. This gas, however, is very rich in methane and ethane, has a high heating value [about 9500 kcal/cu m (1050 Btu/cu ft)] and would be utilized as process fuel.

No information was available on the quantity of the shift reactor condensate stream. The condensate is not, however, expected to be a significant source of pollution as most of the soluble organics in the synthesis gas were removed in the pyrolysis water scrubber.

The gaseous effluent from the methanol devolatilizing column is a small stream, accounting for only 0.4 percent of the waste feed. The stream contains volatile hydrocarbons, however, and would be burned with the purge gas as a fuel.

The liquid dewatering bottoms contain heavy organic ends, soluble methanol, water, and some higher alcohols. The heavy ends would likely be separated from the water fraction and could be utilized as a fuel. The water fraction would have a high COD and a high concentration of methanol and may require treatment before discharge.

Scenario No. 2 (South)--

In the South, the state of Louisiana was selected as one of the regions for the scenario study due to the availability of significant quantities of bagasse and slash pine forest residue. Approximately 2.5 million metric tons of bagasse and 8.5 million metric tons of forest residue are generated annually in Louisiana.(183) Not all of these wastes are available as feedstock for energy conversion, as a substantial portion (estimated to be 50 percent) of the bagasse is used as a fuel or in the manufacture of particle board.(184) Also, some of the forest residues are used for miscellaneous purposes, such as in naval stores production. The wastes are in sufficient quantity, however, to provide a year-round supply of raw feedstock to an energy conversion plant.

Both the bagasse and forest residue are high in cellulose (about 24 percent, wet basis) and water (about 50 percent). In view of these physical characteristics and the burgeoning petrochemical demands of Louisiana and Texas, the energy conversion process chosen as the most applicable for this region is hydrolysis with subsequent fermentation to ethanol. Of the hydrolysis processes, acid-based hydrolysis was selected over enzymatic hydrolysis due to the significantly shorter residence times associated with the acid-based system and its more advanced stage of development. Although not demonstrated on larger than a bench-scale apparatus, a continuous mode of operation was chosen over the batch operation due to the shorter residence times and the potential for higher theoretical sugar yields.(128)

Process description--A summary of major features of the waste feed and the hydrolysis fermentation process is presented in Table 77.

All acid-based hydrolysis processing to date on the pilot plant or commercial scale has been of the batch type. However, studies on the kinetics of hydrolysis and subsequent destruction of the fermentable sugar molecule

$$\text{cellulose} \xrightarrow{k_1} \text{fermentable sugar} \xrightarrow{k_2} \text{decomposed sugar}$$

reveal that the rate of hydrolysis and destruction are a function of the reaction temperature, and that with increasing temperature the rate of hydrolysis increases faster than the rate of destruction.(128) It was thus concluded that high reaction temperatures and short residence times should result in the highest theoretical sugar yields. The range of reaction times and lack of reaction control, characteristic of batch-type operations, make the achievement of maximum theoretical sugar yields nearly impossible. To ensure closer control of the operating conditions and subsequently the reaction kinetics, a continuous isothermal plug flow hydrolysis reactor was proposed.(128) With this reactor, hydrolysis and destruction during a rapid heat-up step could be minimized, and when the desired reaction temperature is reached the reaction could be carried out with maximum selectivity for the sugar. Based on bench-scale, experimental work, a commercial size process was conceptualized for hydrolyzing municipal refuse.(128) This process is described briefly in the section on acid-based hydrolysis and is chosen as the model on which the selected wood residue-bagasse hydrolysis-fermentation process is based.

A simplified process flow schematic is shown in Figure 55, and an overall material balance is given in Table 78. The raw bagasse and wood chip mixture will be initially pulverized to form a 50 percent water slurry by a process similar to the Black Clawson "Hydrasposal" process. The slurry stream will be diluted to a 7:1* liquid-to-solid ratio with water, and steam-heated to the operating temperature of 230 C (459 F). Sufficient sulfuric acid will be added to the slurry to make a 0.4 percent solution. The resulting slurry will be introduced via a screw feeder into one of seven 5-meter long by 0.5-meter in diameter (15 feet long by 2 feet in diameter) continuous-flow hydrolysis reactors. Reactor residence time will be about 1.2 minutes. On discharging from the reactors the product slurry will be cooled to 100 C by flashing in a series of chambers, neutralized by limestone, filtered, and cooled further to 40 C by the preparation water in countercurrent heat exchangers.

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* This ratio is an engineering judgement only and has not been substantiated by experimental research.

TABLE 77. SUMMARY OF BAGASSE AND FOREST RESIDUE TO ETHANOL PROCESS

(South Louisiana Region)

Waste Feedstock

Characteristic of Waste:

Type of waste - bagasse (33 percent) and slash pine forest residue (67 percent)

Moisture content - bagasse, 50 percent; slash pine residue, 50 percent

Ash content - bagasse, 3.0 percent; slash pine residue, 0.5 percent (dry basis)

Cellulose content - bagasse, 24.3 percent; slash pine residue, 24.0 percent (wet basis)

Approximate bulk density - bagasse 200 kg/m^3 (13 lb/cu ft); slash pine residue, 600 kg/m^3 (40 lb/cu ft)

Method of Harvesting:

The forest residue will be harvested as described for Scenario No. 1. The bagasse residue is a by product of the sugar cane processing plants and some is used as fuel and as a raw material for fiberboard production. The remainder (assumed to be about 50 percent) will be collected and transported to the central energy conversion plant.

The sugar cane will be harvested seasonally, and since the bagasse is more susceptible to deterioration and fungus attack than the forest residue, during the harvest season the relative proportion of bagasse feedstock will be increased.

Geographical Aspects of Waste:

Location of waste source - the bagasse is produced in the southern sector of the state. The commercial forestlands lie predominantly in the central and northern sectors of the state.

Geographical density of waste - the density of bagasse is assumed to be 8 metric tons per acre. Based on a total of 316,000 acres devoted to the production of sugar contained within a total estimated land area of 4 million acres, and assuming that 50 percent of the bagasse is not utilized as fuel or for fiberboard production, the effective geographical density of bagasse is estimated to be 0.3 metric tons/acre per year.

TABLE 77. (continued)

As no information could be found on the average density of forest residues for the Southern states, an effective density of 0.5 metric tons per acre year was chosen. This estimate was based on the value of 0.32 metric tons per acre year calculated for the northeast region adjusted to account for the comparatively higher growth rates of wood in the South.

Energy Conversion Plant

Type of Plant:

Continuous acid hydrolysis with fermentation to ethanol.

Product:

Ethanol

Size:

3000 metric tons per day (2000 metric tons per day of forest residue, 1000 metric tons per day of bagasse). Assuming a 55 percent of theoretical yield of sugar (glucose) and a 95 percent fermentability, approximately 204 metric tons per day of 95 percent ethanol will be produced.

Geographical Location:

In South Central Louisiana. Based on the estimated effective geographical densities of 0.5 and 0.3 metric tons per acre for the forest residue and bagasse respectively, and assuming a reasonably uniform distribution of the residue within the harvest region, sufficient feedstock should be available to supply the plant with 3000 metric tons per day within a radius of about 80 miles from the plant.

Storage Facilities:

Area will be provided for 3 days of open storage of wood chips and 3 days of sheltered storage of bagasse. The wood chips will constitute a mound 35 meters square (125 feet square) by 8 meters high; the bagasse will require two covered, ventilated storage facilities 6 meters high (21 feet) by 35 meters square (125 feet square).

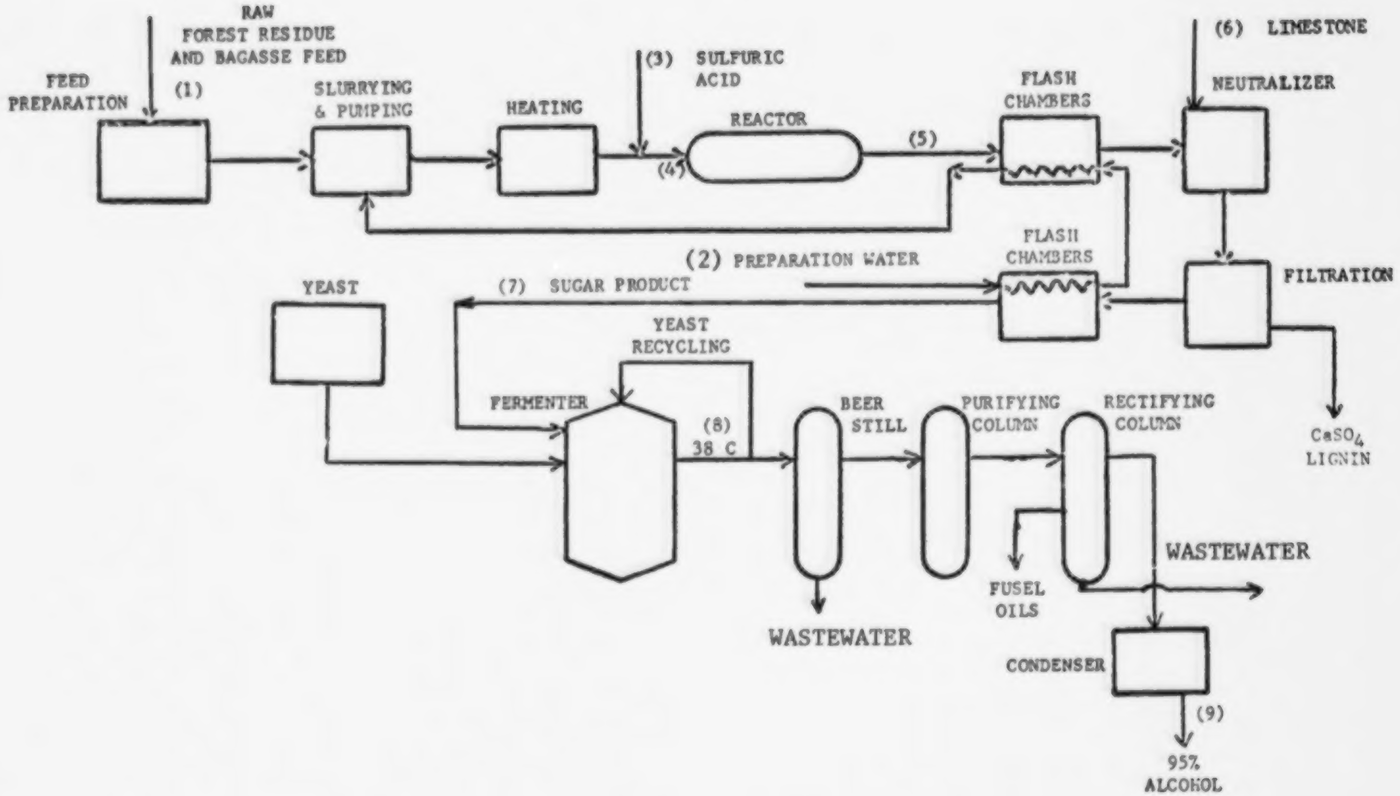
RAW
FOREST RESIDUE
AND BAGASSE FEED
(1)
FEED
PREPARATION
SLURRYING
& PUMPING
HEATING
(3) SULFURIC
ACID
(4)
REACTOR
(5)
FLASH
CHAMBERS
(6) LIMESTONE
NEUTRALIZER
(2) PREPARATION WATER
FLASH
CHAMBERS
FILTRATION
$CaSO_4$
LIGNIN
YEAST
(7) SUGAR PRODUCT
YEAST
RECYCLING
FERMENTER
(8)
38 C
BEER
STILL
WASTEWATER
PURIFYING
COLUMN
RECTIFYING
COLUMN
FUSEL
OILS
WASTEWATER
CONDENSER
(9)
95%
ALCOHOL

Figure 55. Process flow schematic of hydrolysis - fermentation process.

TABLE 78. MATERIAL BALANCE FOR HYDROLYSIS - FERMENTATION PROCESS

Basis: 3000 metric tons per day raw forest residue and bagasse

Stream	Weight Percent	Metric Ton
Stream (1) Biomass Feed		
Forest Residue (Slash Pine)		
Cellulose	24	480
Water	50	1000
Other organics	26	520
Total	100.0	2000
Bagasse		
Cellulose	24.3	243
Water	50	500
Other organics	25.7	257
Total	100.0	1000
Stream (2) Water		
		9000
Stream (3) Sulfuric Acid		
98 percent		50
Stream (4) Reactor Feed		
Cellulose	6	723
Water	87.1	10,500
Unhydrolyzables	6.5	777
Sulfuric acid	0.4	50
Total	100.0	12,050
Stream (5) Reactor Effluent		
Fermentable sugar product	3.3	400
Water	87.1	10,500
Unhydrolyzables	6.5	780
Sulfuric acid	0.4	50
Unreacted cellulose	1.4	170
Decomposed sugar	1.3	150
Total	100.0	12,050
Stream (6) Limestone		
$CaCO_3$		52

TABLE 78. (continued)

Stream	Weight Percent	Metric Ton
Stream (7) Sugar Product		
Fermentable sugar	3.7	400
Water	94.9	10,400
Decomposed sugar	1.4	150
Total	100.0	10,950
Stream (8) Solution from Fermenter		
Alcohol	1.8	194
Water	96.7	10,400
Other	1.5	150
Total	100.0	10,744
Stream (9) Alcohol Product		
Alcohol	95	194
Water	5.0	10
Total	100.0	204

Based on a low cellulose content in the feedstock of 48 percent (dry basis) and a sugar yield of 55 percent of theoretical yields, approximately 400 metric tons of 3.7 percent sugar slurry will be produced daily.

A flow chart of the fermentation process is also shown in Figure 55 and the material balance is listed in Table 78. Industrial scale fermentation of wood hydrolyzate was practiced approximately 30 years ago but only on batch-type processes. However, the subsequent development of improved process technology has resulted in the introduction of a continuous molasses fermentation process.(128) In view of the proven performance of this continuous fermentation process, a similar process, based on wood hydrolyzate feed, is believed to be technologically feasible and is selected as the model process for this scenario.

The sugar product solution is pumped to the fermentor where the yeast (approximately 1 percent by volume) is added. The solution is permitted to ferment for 24 hours after which time the yeast is withdrawn from the fermented sugar solution and recycled. The alcohol product is separated from solution by distillation. The overhead vapors from the distillation column (beer still) are condensed and conducted to the purifying column. Effluent liquor from this column flows to the rectifying column where 95 percent alcohol is taken off the top of the column and passed through a condenser. Fusel oils are taken off near the bottom of the column and sold as impure amyl alcohol. The bottom of the column discharges the water waste.

Environmental aspects--Waste streams generated in the process are discharged from three areas: the hydrolyzate filters, the fermentation product beer still, and rectifying column.

The filter cake from the hydrolysis step is composed primarily of unreacted cellulose, residual lignin (unhydrolyzables), the $CaSO_4$ resulting from lime neutralization, and entrained water, product, and decomposed sugars. Approximately 1150 metric tons/day of this material will require treatment. The liquid portions will be high in BOD but will be easily treated by conventional waste treatment scheme. The solid portion, high in lignin, might be air dried and used to meet process demand for steam and/or electric power.

The two streams leaving the fermentation section of the plant are the beer still and the rectifying column bottoms. The sum of these two streams will be approximately 10,000 metric tons per day (11,000 ton/day). The beer still bottoms will contain yeast particles not recaptured for recycle, as well as sugars and mixed alcohol products. After filtration, the solids portion remaining is often sold as cattle feed supplement in current industrial practice. Since this scenario is located within reasonable shipping distance of major feedlot operations, this market would seem to be readily available to this hypothetical plant as well.

The recovery of the beer still bottoms will not grossly alter the volume of wastewater to be treated. The BOD load will be high, but, again, it should be very susceptible to conventional wastewater treatment techniques. Alternatively, an algae-growing process system might be considered. The recovered algae from such a system would be high in protein and integratable with the beer stills bottoms, in a cattle feed marketing strategy.

Scenario No. 3 (West Coast)--

The region of the West Coast (primarily southern California) represents an area which could successfully combine ocean farming of kelp with refuse from urban areas located near the coast, as feedstocks for an energy conversion plant.

The high moisture content of the material indicates that a thermochemical conversion process would be less efficient than a biochemical process. The two primary biochemical processes that are considered as possible commercial processes are hydrolysis-fermentation and anaerobic digestion. Due to the non-uniform composition of urban refuse and the deleterious effect it would have on fermentation yields, anaerobic digestion of the feedstock for conversion to methane was selected as the more appropriate process.

Two-stage digestion was selected for evaluation in this scenario. The partial pressure of methane in the gas collected from the second stage is significantly greater than that collected from a single-stage system. This may be due to the relatively high pH (7.5) which occurs in the second stage. At this pH, the carbonic acid equilibria is shifted to the right, and more CO_2 is present in the aqueous phase, as opposed to the gaseous phase. Therefore, the partial pressure of CO_2 is reduced, and the partial pressure of CH_4 is increased. The increased concentration of methane and the higher heating value of the gas results in reduced operating costs for gas purification for the two-stage system relative to a single-stage system.

Process description--A schematic flow diagram of the process conceptualized for Scenario 3 is presented in Figure 56. Relevant data used to construct the scenario are summarized in Table 79; the associated material balance is presented in Table 80.

The two types of feedstock, urban refuse and kelp, are collected and transported to the plant site. Each of the feedstocks is pretreated separately before entering the first-stage digester. Urban refuse is shredded, ferrous metals are separated, the material is screened, air classified, and shredded a second time. Ferrous metals, non-ferrous metals, and glass are recovered during the preprocessing steps.

Kelp is pretreated with calcium ion and pressed to remove salt. Potassium chloride, sodium carbonate, and sodium sulfate are extracted from the brine. Sugar syrups are recovered from the juice in the pressing operation.

Pretreated refuse and kelp is mixed and pumped to the first-stage digester. The residence time in the first-stage is approximately 4 days. The required volume of the digester is 69,000 cu m (2.44 x 10^6 cu ft). Effluent from the first stage is separated and the liquids are transferred to the second stage. The required volume of the second stage digester is 172,500 cu m (6.1 x 10^6 cu ft). Gas is collected from the second-stage digester and purified. Effluent from the second stage is separated and the solids are combined with first-stage solids and recycled to the mixing tank.

Environmental aspects--The discharge streams from the process are (1) liquid effluent from the digesters, (2) sludge from the digesters, (3) gas from the first stage which primarily contains carbon dioxide, and possibly (4) waste brine from the kelp pretreatment section. The liquid stream from the digester effluent has a relatively high pH (greater than 7.0) and high BOD and COD. The liquid requires secondary treatment before discharging to the sewage system. Liquid waste from the brine processing operation can be recycled to the kelp beds to provide nutrients. If recycling is not economic, the waste brine will require secondary treatment. Although most of the solids are recycled, 3362 metric tons per day are discharged as sludge from the system to avoid buildup. The sludge can be used as a fertilizer or disposed of by landfill.

Scenario No. 4 (Midwest)--

Ohio was selected as representative of the Midwest region because of the large area of potentially reclaimable strip-mined land and the growing demand for electric power. As discussed in the previous section on the selection of regions, a viable method of reclaiming the strip-mined land and producing an energy crop is by planting fast-growing, nitrogen-fixing trees, e.g., European alders. These trees may be cropped every 5 to 6 years and utilized as a feedstock for an energy conversion process.

One energy conversion process with an application for this region is the CPU-400 gas turbine electric generator. This system can utilize the cropped wood and generate peak load electric power for the Ohio-Western Pennsylvania region. The wood feed should be more suitable as a feedstock for the fluidized-bed combustor than municipal solid waste, as the wood is free of aluminum and

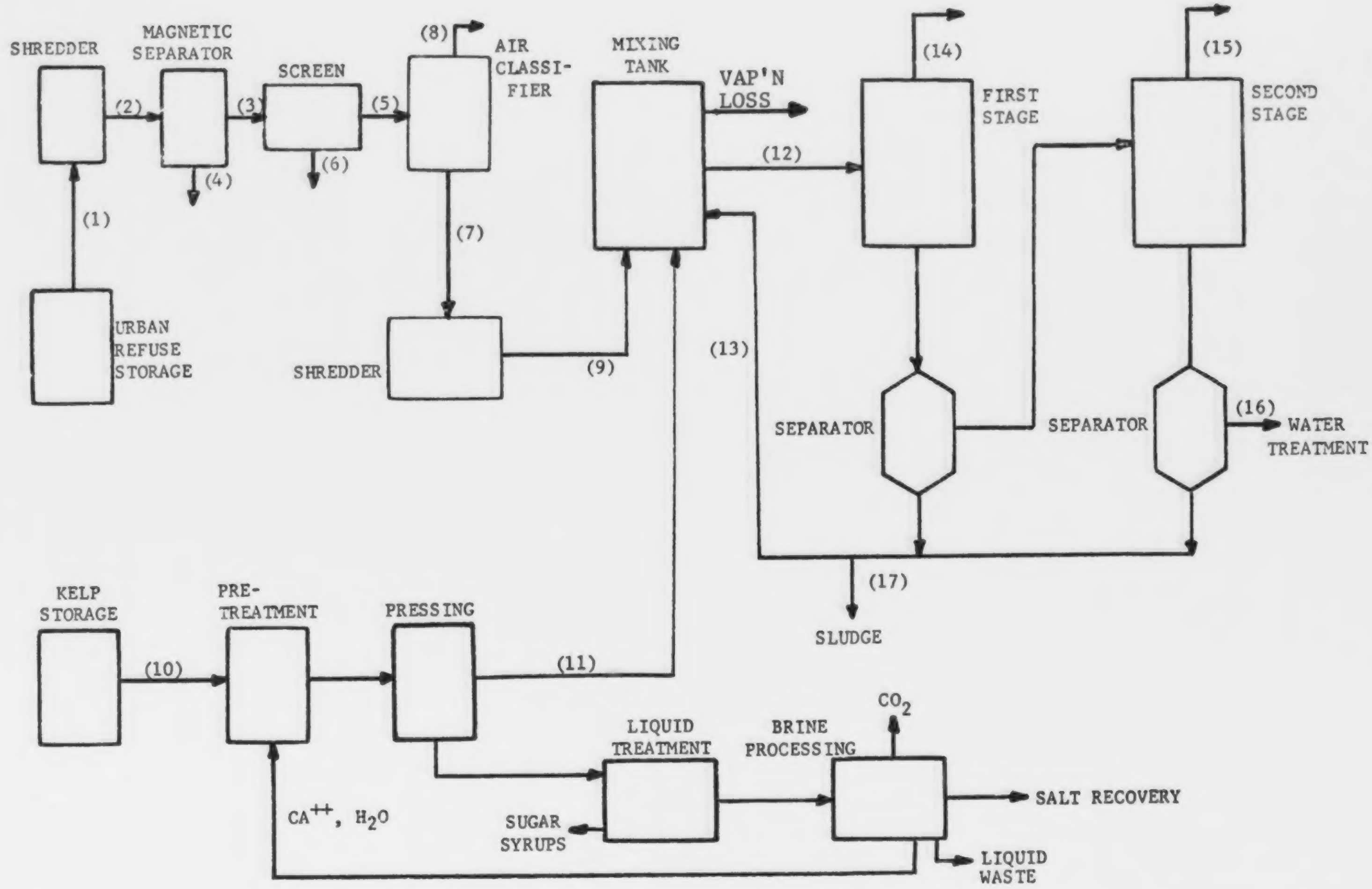
SHREDDER
MAGNETIC SEPARATOR
SCREEN
(8)
AIR CLASSI-FIER
MIXING TANK
VAP'N LOSS
(14)
FIRST STAGE
(15)
SECOND STAGE
(2)
(3)
(5)
(4)
(6)
(12)
(1)
(7)
URBAN REFUSE STORAGE
SHREDDER
(9)
(13)
SEPARATOR
SEPARATOR
(16)
WATER TREATMENT
(17)
SLUDGE
KELP STORAGE
PRE-TREATMENT
PRESSING
(10)
(11)
LIQUID TREATMENT
BRINE PROCESSING
CO_2
SALT RECOVERY
CA^{++}, H_2O
SUGAR SYRUPS
LIQUID WASTE

Figure 56. Flowsheet of two-stage anaerobic digestion process.

TABLE 79. SUMMARY OF KELP AND URBAN WASTE TO SNG PROCESS

Waste Feedstock

Characteristics of Waste:

	Kelp	Urban Refuse (before screening)
Moisture Content	87.5%	25%
Ash Content	5.2%	3% (after screening and shredding)
Density	1009 kg/cu m (62.2 lb/cu ft)	486 kg/cu m (30 lb/cu ft)
Cellulose Content	0.2%	46%
Volatile Solids	7.3	57%

Method of Harvesting Waste:

Kelp will be harvested with special boats which will be equipped to cut off the tops of the fronds and transport the harvested material to the processing plant. Kelp is currently harvested from natural beds with boats of this type. Urban waste will be collected in the usual manner and transported to the processing plant in trucks.

Geographic Aspects of Waste:

Seven hundred forty metric tons of kelp can be produced per hectare of ocean area (330 tons/acre/year). Therefore, the area required to supply the plant with 5000 metric tons of kelp/day (assuming 330 days/yr) is 2230 hectares (5510 acres). It should be noted that while 5000 tons/day is on a wet basis, this flow represents about 600 tons/day on a dry basis or approximately 14 percent of the solid waste flow, dry basis.

Five thousand metric tons/day of urban refuse can be supplied from an area with a moderately large population density. The city of Los Angeles has a population density of approximately 23 persons/hectare (9.5 persons/acre).(185) Assuming 0.5 kg of refuse is produced per person per day, 4.3×10^5 hectares (1.1×10^6 acres) would be required to support the plant.

In more conventional terms, at 0.5 kg per person per day, a population of about 10 million, or essentially the entire population of the Los Angeles area would be required. On the basis of actual data, Los Angeles city produces on the order of 4600 metric tons/day (5000 tons/day),(186) with the difference probably due to the

TABLE 79. (continued)

industrial waste component. However, it is clear that a plant of this size would represent a major commitment from the second largest city in the nation. Alternatively, the relative percentage of feedstock supplied from the kelp could be increased.

Energy Conversion Plant

Type of Plant:

Two-stage anaerobic digestion

Major Product:

SNG

By-Products from Urban Waste Feed:

Ferrous, nonferrous metals, glass

By-Products from Kelp Feed:

Sugar, salts, fertilizer

Size:

10,000 metric tons per day, 50% kelp, 50% urban refuse

Based on a potential methane production of 0.3 cu m/kg (dry basis) (5.5 scf/lb) of kelp and 0.4 cu m/kg (6 scf/lb) of urban refuse, the plant will produce approximately 986,000 cu m of methane per day.

Geographical Location:

West Coast (southern California)

Storage Facilities:

One week's storage facilities for kelp would be available at the plant site. This would require 35,000 cu m (1.2 x 10^6 cu ft) of storage. Facilities for 1 week storage of urban refuse requires 72,000 cu m (2.5 x 10^6 cu ft).

TABLE 80. MATERIAL BALANCE OF TWO-STAGE ANAEROBIC DIGESTION

Stream	Composition	Metric Tons
Stream 1	Urban Refuse	
	Moisture	1250
	Organics	2500
	Other	1250
	Total	5000
Stream 2		
	Total	5000
Stream 3		
	Total	4688
Stream 4		
	Metals	312
Stream 5		
	Total	4225.5
Stream 6		
	Glass, Ash	462.5
Stream 7		
	Total	3302.5
Stream 8		
	Organics	375
	Metals	84
	Glass	95.5
	Plastics	75
	Ash	106
	Moisture	187.5
		923.0
Stream 9		
	Organics	2126
	Metals	4
	Glass	17
	Plastics	75
	Ash	18.5
	Moisture	1062
		3302.5

TABLE 80. (continued)

Stream	Composition	Metric Tons
Stream 10		
	Total	5000
Stream 11		
	Volatile Solids	340
	Water	4375
	Ash	240
	Total	4955
Stream 12		
	Volatile Solids	2466
	Water	14437
	Other	354.5
	Total	17257.5
Stream 13		
	Solids	1466
	Water	9000
	Total	10466
		cu m
Stream 14		
	Carbon Dioxide	296,000 cu m
	Methane	(assume zero)
		296,000 cu m
Stream 15		
	Carbon Dioxide	246,600 cu m
	Methane	986,400 cu m
		1,233,000 cu m
		Metric Tons
Stream 16		
	Water	3075
Stream 17		
	Solids	1000
	Water	2362
	Total	3362

thus obviates one of the major problems plaguing the existing CPU-400 pilot plant, that of aluminum oxide particulate removal.

Process description--The characteristics of the waste feeds and the energy conversion process are summarized in Table 81. Figure 57 is a schematic flow diagram of the electric generating facility and Table 82 gives a material balance of the facility based on a daily biomass waste feed of 350 metric tons. A detailed description of the CPU-400 gas electric generator is provided in Section 5 and is not addressed in this discussion. Basically, the facility would consist of a fluidized-bed combustor, the cyclone separators, a granular filter and two-stage turbine compressor and electrical generating unit. The facility would operate at peak load periods (approximately 8 hours per day) and during this period would generate approximately 16.5 MW of electrical power.

Environmental aspects--The exhaust gases from the generator should be low in SO_x and NO_x and particulates and should not require control equipment. The other waste streams, the ash, and captured particulates would be disposed of in a landfill.

Scenario No. 5 (Midwest)--

In the Midwest, the State of Kansas was selected as one of the regions to be analyzed in this study because of the availability of large quantities of agricultural wastes. Wheat crops are harvested twice a year in this area, leaving wheat straw as a residue. Following collection and proper storage of this material, it would be available as a potential feedstock to an energy conversion process. Large numbers of feedlots exist in the same area, providing sources of easily collectable manure which would be available as a supplemental feedstock. Due to the relatively high moisture content and low cellulose content of the potential feedstocks, a biochemical conversion process was chosen to be evaluated in this study. Of the possible products which can be produced from biochemical processes (methane, ethanol, butanol), methane was chosen as a product because of the potentially large demand for grain drying and the close proximity of major pipelines leading to the more populous East; single-stage anaerobic digestion to produce methane was selected as the conversion process.

Process description--Figure 58 is a simplified process schematic for the single-stage anaerobic digestion process. Pertinent general information is summarized in Table 83 while Table 84 presents a material balance. The process is modified from the work of Singh.(145) Both feedstocks are removed from storage, water is added to the mixture which is then pumped to the digester. Some pretreatment, such as size reduction may be required for wheat straw to increase the methane production. Assuming a retention time of ten days, the required volume is 750,000 cu m (2 x 10^8 gal). The effluent from the digester is filtered and the solids are either used as fertilizer or landfill. Eighty percent of the liquid is recycled to the mixing tank. The remaining 20 percent is sent to a water treatment plant. The BOD concentration of this stream is approximately 500 mg/ℓ.

Environmental aspects--Slurry from the digester is separated into two streams by filtration. The filter cake contains 50% solids and has a high BOD concentration (500-1000 mg/ℓ). The filter cake (3113 metric tons/day)

TABLE 81. SUMMARY OF CONVERSION OF WOOD AND CORN RESIDUE TO ELECTRICITY PROCESS

(Midwest Region - Ohio)

Waste Feedstock

Characteristics of Biomass Feed:

Type - European alder (80%); corn residue (20%)

Moisture content - Alder, 50 percent; corn, 50 percent

Ash content - Alder, 3 percent; corn, 2 percent

Sulfur content - Alder, 0.1 percent; corn, 0.17 percent

Approximate heating value - Alder, 2600 kcal/kg (4,675 Btu/lb);
corn, 2600 kcal/kg (4,675 Btu/lb)

Approximate bulk density (green) - chipped alder, 800 kg/cu m
(54 lb/cu ft); corn, 400 kg/cu m
(27 lb/cu ft)

Method of Harvesting:

The alders will be harvested on a 6-year staggered rotation period on a year-round schedule. A silage-type harvester will crop the trees and feed them to a chipper where they will be reduced to chips. The wood chips will then be transported by truck to the power generating plant for storage and subsequent use.

The corn residue will be harvested seasonally by a combine that will collect both the grain and residue simultaneously. The residue will be ground and compressed and loaded into a truck for transport to the power generating plant.

Due to the lower bulk density of the corn residue as opposed to wood chips and the susceptibility of corn residue to deterioration, during the corn harvesting seasons the relative proporation of corn residue feedstock will likely be increased.

Geographical Aspects of the Waste:

Location of waste sources - as explained in the introduction to this section, the European alders will be planted on the reclaimed strip-mined land in Ohio. This region is centered primarily in the eastern section of the State where approximately 121,500 hectares (300,000 acres) have been strip-mined.(187)

The corn fields are assumed to be scattered in the more agriculturally productive pockets of the region.

TABLE 81. (continued)

Geographical density of waste - based on a 6-year rotation period and a yield of 15 metric tons of alder wood per acre per year, the average harvestable field density would be 2.5 metric tons per acre per year. Assuming 20 percent of the surface area in the selected region is suitable for strip mining and has been reclaimed or is amenable to reclaiming, the effective geographical density of the harvestable alder crop is 0.5 metric ton per acre per year.

The average field density of the corn residue crop is assumed to be 2.5 metric tons per acre per year. Assuming 10 percent of the surface area in the selected region is utilized for corn growth, the effective geographical density of the corn residue is 0.25 metric ton per acre per year.

Energy Conversion Plant

Type of Plant:

Gas turbine electric generator (CPU-400)

Product:

Electricity for peak load demand

Size:

Three hundred fifty metric tons per day (an average annual balance of 280 metric tons per day of wood chips and 70 metric tons per day of corn residue) - equivalent to 5.5 MW of continuous power or 16.5 MW of peak power based on a larger generator operating only during peak load periods for 8 hours per day.

Geographical Location:

Centrally located in the strip-mining region of eastern Ohio. Based on: (1) an effective geographical density for harvestable alder of 0.5 metric tons per acre per year; and (2) 63 metric tons per day of green wood waste or corn residue will generate approximately 1 MW-hr of electrical energy,* sufficient feedstock should be available, on a continuous year-round basis, within a radius of 25 miles from the central plant.

TABLE 81. (continued)

Storage Facilities:

Area will be provided for 3 days of open storage of wood chips and corn residue. The 1,060 metric tons of waste will occupy a volume of 1,470 cu m (53,000 cu ft). This volume would represent a mound approximately 8 meters high by 13 meters on a side (27 ft high by 45 ft on a side). Special consideration must be given to the corn residue; it is more perishable than wood chips and might require a covered, ventilated storage facility, e.g., a silo.

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*This is an estimate based on the results of the pilot plant work on the CPU-400 process at Menlo Park, California.(188)

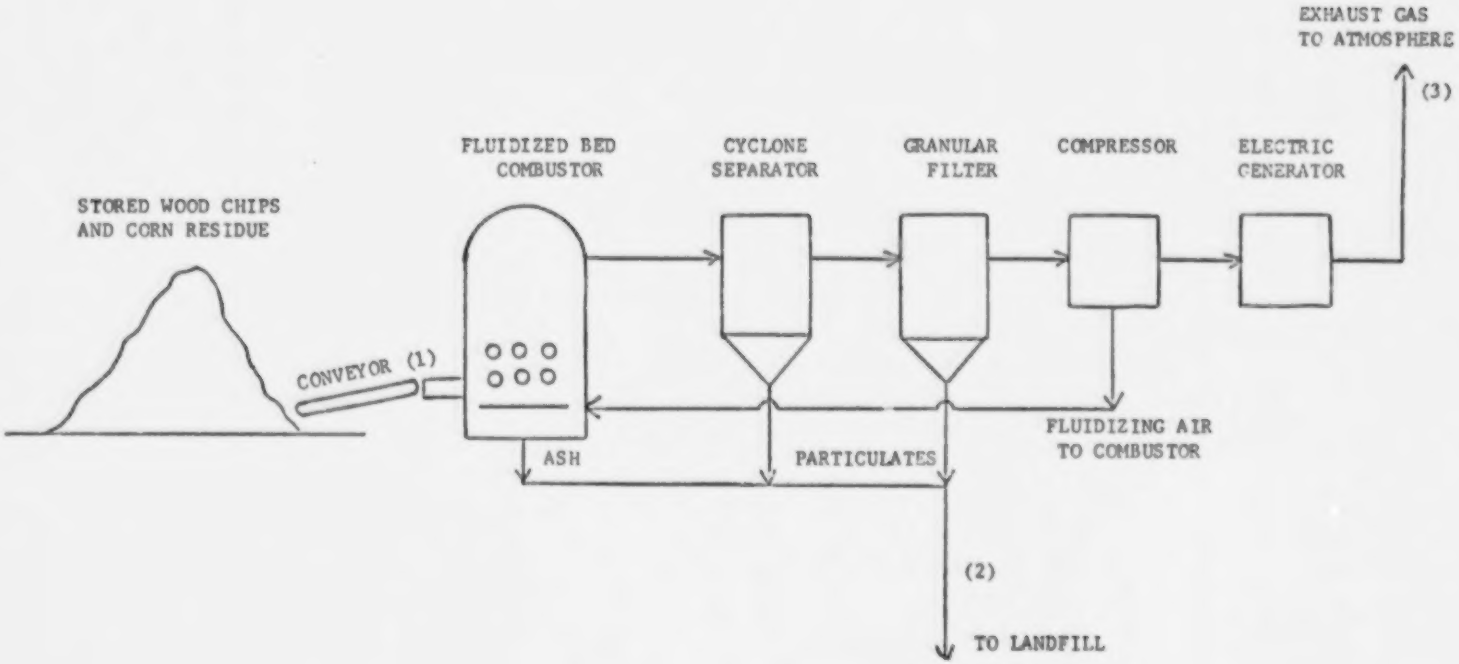

EXHAUST GAS
TO ATMOSPHERE
(3)
FLUIDIZED BED
COMBUSTOR
CYCLONE
SEPARATOR
GRANULAR
FILTER
COMPRESSOR
ELECTRIC
GENERATOR
STORED WOOD CHIPS
AND CORN RESIDUE
CONVEYOR (1)
FLUIDIZING AIR
TO COMBUSTOR
ASH
PARTICULATES
(2)
TO LANDFILL

Figure 57. Process flow schematic of gas turboelectric generating system.

TABLE 82. MATERIAL BALANCE FOR GAS TURBOELECTRIC GENERATION PROCESS

Basis: 350 Metric Tons Per Day Chipped Wood and Corn Residue Feed

Stream	Weight Percent	Metric Ton
Stream (1) Biomass Feed)		
Chipped European Alder (280 metric tons per day)		
Organic compounds	46.7	130
Water	50.0	140
Ash	3.0	10
Sulfur	0.1	<1
Nitrogen	0.2	<1
Total	100.0	280
Corn Residue (70 metric tons per day)		
Organic compounds	47.6	33
Water	50.0	35
Ash	2.0	1
Sulfur	0.17	<1
Nitrogen	0.2	<1
Total	100.0	70
Stream (2) Ash and Particulates		
Predominantly oxides of silica, calcium, and aluminum		~24
Stream (3) Exhaust Gases to Atmosphere		
Predominantly water, carbon dioxide, and nitrogen		~5000(a)

(a) Assumes 10 percent excess air.

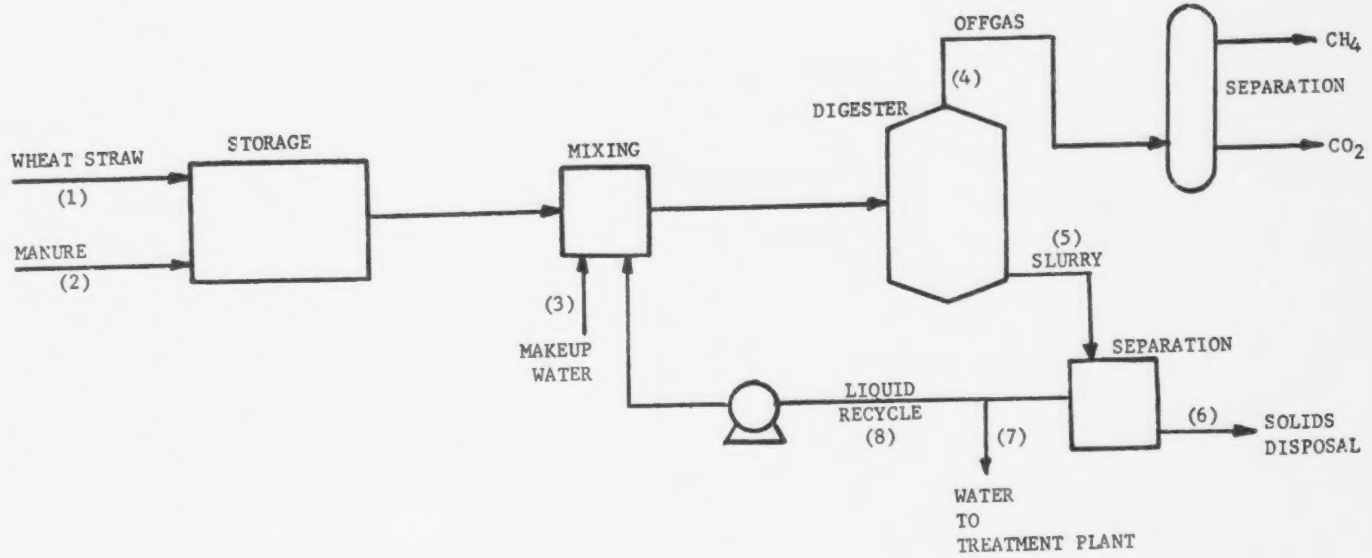

WHEAT STRAW
(1)
MANURE
(2)
STORAGE
MIXING
(3)
MAKEUP WATER
DIGESTER
OFFGAS
(4)
CH_4
SEPARATION
CO_2
(5)
SLURRY
SEPARATION
LIQUID RECYCLE
(8)
(7)
WATER TO TREATMENT PLANT
(6)
SOLIDS DISPOSAL

Figure 58. Flowsheet of single-stage anaerobic digestion plant.(145)

TABLE 83. SUMMARY OF WASTE FEEDSTOCKS FOR ANAEROBIC DIGESTION PLANT

Waste Feedstock

Characteristics of Waste:

	Manure	Wheat Straw
Moisture Content	85% (fresh)	12.2% (field dried)
Ash Content	3.1%	7.2% (dry)
Density	1005 kg/cu m (62 lb/cu ft)	778 kg/cu m (48 lb/cu ft)
Cellulose Content	17% (dry)	53.6%
Methane Production	0.2 cu m/kg V.S. (3.6 cu ft/lb V.S.)	0.4 cu m/kg V.S. (7.0 cu ft/lb V.S.)

Method of Harvesting:

Wheat is harvested twice a year. The residue would be collected and stored. Manure would be collected from feedlots on a daily or weekly basis and would not require long storage periods.

Geographical Aspects:

Location - Kansas	Manure	Wheat Straw
Availability -	22-27 kg/animal/day (wet)	3.5 metric tons/hectare/yr
	(48-60 lb/animal/day)	(1.5 tons/acre/yr)
	6.4×10^6 animals	4.7×10^6 hectare (11.6×10^6 acres)

16.4×10^6 metric tons/yr (18×10^6 tons/yr) of wheat straw are available. Based on 330 days per year, this represents 49,700 metric tons/day (54,500 tons/day)

The quantity of manure available on a yearly basis is 52.8×10^6 metric tons/yr (58.2×10^6 tons/yr) or 160,000 metric tons/day (176,000 tons/day).

TABLE 83. (continued)

Energy Conversion Plant

Type of Plant:

Single-stage anaerobic digestion plant

Product:

Methane

Size:

10,000 metric tons/day (11,025 TPD)

Feed Rate:

Manure - 5000 metric tons/day (5513 TPD)
Wheat Straw - 5000 metric tons/day (5513 TPD)

Storage Requirements:

Manure - 7 day storage: 35,000 cu m (1.24×10^6 cu ft)
Wheat Straw - 6 month storage: 1×10^6 cu m (38×10^6 cu ft)

Digester Temperature:

35-37 C

TABLE 84. MATERIAL BALANCE FOR SINGLE-STAGE ANAEROBIC DIGESTION PROCESS

Basis: 10,000 metric tons/day (11,025 ton/day)

Stream	Composition	Metric Tons	
Stream 1	Wheat Straw		
	Moisture	610	
	Volatile Solids	4,030	
	Ash	360	
	Total	5,000	
Stream 2	Manure		
	Moisture	4,250	
	Volatile Solids	595	
	Ash	155	
	Total	5,000	
Stream 3	Water Makeup		
	Water	7,073	
Stream 4	Digester Off-Gas		Cubic Meters
	Methane	589	(822,000 CM/D)
	Carbon Dioxide	1,097	(548,000 CM/D)
	Water	142	
	Total	1,837	
Stream 5	Slurry		
	Solids	5,218	
	Water	46,962	
	Total	52,180	
Stream 6	Solids Disposal		
	Solids	3,000	
	Water	3,000	
	Total	6,000	
Stream 7	Water to Treatment Plant		
	Solids	443	
	Water	8,793	
	Total	9,236	
Stream 8	Liquid Recycle		
	Solids	1,773	
	Water	35,171	
	Total	36,944	

can be disposed of either by landfill or combustion of the solids for heat recovery. The filtrate contains 4.8% solids and 9,236 metric tons/day are sent to the secondary treatment plant.

The quantity of water required for the process is 7,073 metric tons/day.

Scenario No. 6 (West-Urban Center)--

The municipal solid waste chosen as the biomass energy source for the western urban center may be converted to utilizable energy by almost any of the previously described thermochemical processes. Of the thermal processes, direct combustion for the generation of steam was selected as one of the more appropriate processes for this region. Direct incineration is the most thermally efficient method of converting biomass to energy and is one of the most expeditious means of minimizing the huge quantities of municipal waste. Moreover, steam has a significant potential market in an urban center for use in industry or for municipal heating and cooling.

Process description--A summary of the waste characteristics and the steam generating system is presented in Table 85. Figure 59 is a schematic flow diagram of the heat recovery process and Table 86 gives an estimated material balance based on 5000 metric tons of raw MSW feed.

The facility will consist of (1) a preprocessing unit which will shred the refuse and separate ferrous metals; (2) the refuse storage facilities and conveying system; (3) the heat recovery system, consisting of ten-500 metric-ton-per-day capacity stoker-fired incinerators (similar to that described in the section on urban and municipal solid waste under the heading "Primary Thermochemical Conversion Processes"); (4) an ash collection and transfer system; and, (5) a combustion gas manifolding and cleanup system consisting of a single electrostatic precipitator.

The raw waste will first be shredded in a hammermill and passed through a magnetic separator where the ferrous metals will be removed. The remaining refuse consisting primarily of combustible organics, will be conveyed to the storage facility from where it will be subsequently withdrawn and fed into the incinerators. The combustion gases will pass through the boiler section and economizer and will be manifolded into a single, common exhaust duct for treatment by the electrostatic precipitator. The total gas flow from all ten boilers will be approximately 1100 standard cu m per second (40,000 cfs).

Mobile Biomass-to-Energy Conversion Process

This section involves a preliminary feasibility analysis of a mobile pyrolysis installation designed for remote or rural areas for converting on-site, waste biomass directly to energy or into a utilizable fuel. To help facilitate the conceptualization of the modular process, the following criteria were established on which to base the determination of (1) the type of waste feed, (2) the type of fuel produced, and (3) the specific type of conversion technology.

(1) Simplicity - the process must be functionally simple and easy to operate, preferably by a single operator.

TABLE 85. SUMMARY OF MUNICIPAL SOLID WASTE TO STEAM PROCESS

Waste Feedstock

Characteristics of Waste:

Type of waste - municipal solid waste

Moisture content - 25 percent

Ash content - 14 percent

Sulfur content - 0.2 percent

Heating value - 2700 kcal/kg (5000 Btu/lb)

Bulk density (shredded) - 440 kg/cu m (30 lb/cu ft)

Method of Harvesting:

The municipal waste will be collected daily, on a 5-day per week basis, and transported by truck to conveniently located depots where it will be unloaded and transported by rail to the energy conversion plant.

Energy Conversion Plant

Type of Plant:

A water-walled incinerator, similar to the Chicago Northwest facility

Product:

7×10^5 kg/hr (15×10^5 lb/hr) of 250 psig steam for industrial processing and heating or municipal heating, cooling etc.

Size:

5000 metric tons per day (5600 TPD) of MSW feed.

TABLE 85. (continued)

Geographical Location:

The plant will be located in close proximity to the industrial or municipal market.

Storage Facilities:

Enclosed buildings will be provided for storing the shredded, solid waste for up to 4 days. The volume occupied by 20,000 metric tons of shredded municipal waste is approximately 41,000 cu m (1.5 million cu ft). This quantity of waste will require five storage buildings 6 meters high (20 ft) by 37 meters square (120 ft square).

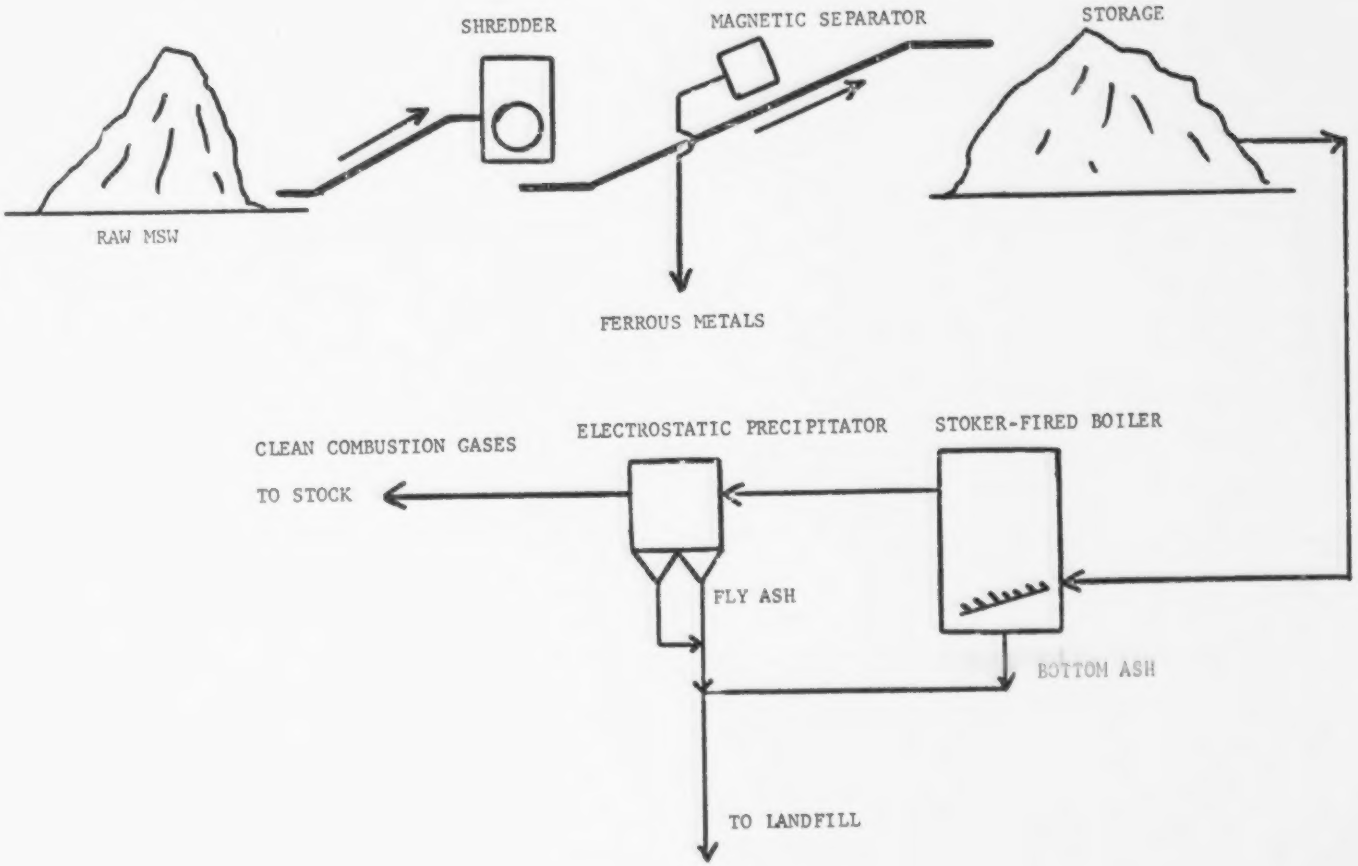

SHREDDER
MAGNETIC SEPARATOR
STORAGE
RAW MSW
FERROUS METALS
CLEAN COMBUSTION GASES
TO STOCK
ELECTROSTATIC PRECIPITATOR
STOKER-FIRED BOILER
FLY ASH
BOTTOM ASH
TO LANDFILL

Figure 59. Process flow schematic for municipal solid waste to steam conversion process.

TABLE 86. MATERIAL BALANCE FOR CONVERSION OF URBAN REFUSE TO HEAT

Basis: 5000 metric tons per day of municipal solid waste (MSW)(189)

Stream (1) Raw MSW	Weight Percent	Metric Tons
Organics	52	2600
Metals		
Ferrous	12	600
Aluminum	1	50
Glass	7	350
Other Inorganics	1	50
Moisture	25	1250
	100	5000
Stream (2) Incinerator Feed		
Organics	59	2600
Metals		
Ferrous	<1	30
Aluminum	1	50
Glass	8	350
Other Inorganics	2	100
Miscellaneous Solids	1	50
Moisture	28	1250
	100	4430
Stream (3) Ferrous Metals		Metric Tons
		570
Stream (4) Ash, Residue and Fly Ash		Metric Tons
Predominantly silica, Aluminum and calcium oxide		>>580
Stream (5) Combustion Gas		Metric tons
Predominantly Carbon Monoxide and Water		95,000[a]

[a] Assumes 10 percent excess air

(2) Maintenance and Operating Requirements - the maintenance and operating requirements must be low.

(3) Preprocessing - a minimal amount of preprocessing of the waste should be required.

(4) Applicability to Different Waste Feed Characteristics - the process should be able to accommodate heterogeneous wastes with varying water and cellulose contents.

(5) Mobility - the modular unit should be compact, light in weight, and mobile.

(6) Environmental Aspects - the operation of the mobile unit and the use of the produced fuel, if any, should introduce minimal secondary environmental problems.

(7) Application - the mobile conversion system should produce energy or a fuel directly utilizable at the remote site with minimal modification requirements for existing equipment.

(8) Practicality - maximum use of established equipment technology and known energy demand should be made.

Consistent with the above criteria, several possible types and applications of mobile energy conversion processes can be eliminated. The biochemical processes (anaerobic digestion, fermentation, etc.) would not be appropriate due to the long residence times and prohibitively large vessel sizes. The more involved primary thermochemical and all secondary processes (hydrogenation, methanol production, etc.) would also be inappropriate as they are too complex to be of practical application on a mobile trailer.

Three operations or processes that may be regarded as suitable candidates are: (1) wood chippers, (2) fuel densifiers, and (3) grain dryers.

(1) Wood Chipper - this would be a mobile unit capable of mulching forest residue into chips to facilitate easier handling and transportation. These devices are commercially available but must be classified as preprocessing methods as they rely on another process for converting the wood chips to energy.

(2) Fuel Densifier - this would be a mobile pyrolysis unit that would convert forest and agricultural residue into a solid fuel with a higher heating value. This process has been demonstrated by Georgia Tech (see the section on the Georgia Tech pyrolysis system) for producing a fuel char on a mobile unit installed on two flat-bed trailers. The merits of the unit as a mobile energy conversion process are questionable, however, as the produced char has limited application as a fuel (not applicable to gas or oil-fired burners), and the loss in net thermal efficiency in converting the wood to char could likely offset the increased heating value of the char.

(3) Agricultural Grain Dryer - this concept would burn crop residue and utilize the hot, cleaned, combustion gases to dry the harvested grain. The unit, as envisioned, would be mounted on a flat-bed trailer and towed from farm to farm where it converts the crop residue into heat for drying the harvested grain. The crop residue would serve as a cheap fuel substitute for natural gas, fuel oil, or propane, which are currently used to supply the energy for drying. Although practiced in large, stationary 2.5 to 5.0 million kcal/hr (10 to 20 million Btu/hr) dryers located at central storage facilities(190), no information was available to suggest the existence of a mobile agricultural residue fueled dryer for farm applications.

Of the above-mentioned energy-conversion alternatives, the system regarded as the most appropriate in view of the eight assessment criteria is the agricultural grain dryer. A more detailed discussion of such a system is presented below.

Agricultural Grain Drying--

This system would be applicable to provide the thermal energy necessary in drying most grain crops, corn, soybeans, oats, rice, etc. The thermal calculations and engineering design for the mobile system are based on the drying of field corn, as corn is not only produced in prodigious quantities but usually requires more drying than most other grains (oats or soybeans) and would thus impose a greater heat or energy load on a drying system. The greater heat load would result in a conservative design estimate which would likely prove adequate for drying most of the other less energy-demanding grain crops.

The system would consist of a conveying mechanism, a feed hopper, a mechanical grate incinerator, multiclone particulate collectors, an ash collector, and a combustion gas discharge duct adaptable to existing corn drying units; a schematic of the system is shown in Figure 60. The corn residue (stalks, leaves, and cob) harvested with the corn would be fed into the incinerator where it would be combusted at about 650 C (1200 F) with air. The hot combustion gas would be passed through the multiclone separators, where the particulates would be removed, through the discharge duct, and into the bottom of the corn dryer.

The fuel characteristics for corn stover are given in Table 87. Based on a heating value of 2600 kcal/kg (4675 Btu/lb) for the corn residue, a 95 percent combustion efficiency, a 25 percent heat loss through the separators and ductwork, a 25 percent net drying efficiency, and the assumption that one kg of corn residue is harvested with each kilogram of shelled corn, a heat balance (shown in Table 88) has been constructed. As can be seen, there is sufficient heat value in the corn residue to dry the grain without the need for supplemental fuel.

Several factors must be resolved before this concept can be regarded as a viable waste-to-energy alternative, however. The thermal efficiency of the entire system and the particulate removal efficiency of the multiclones must

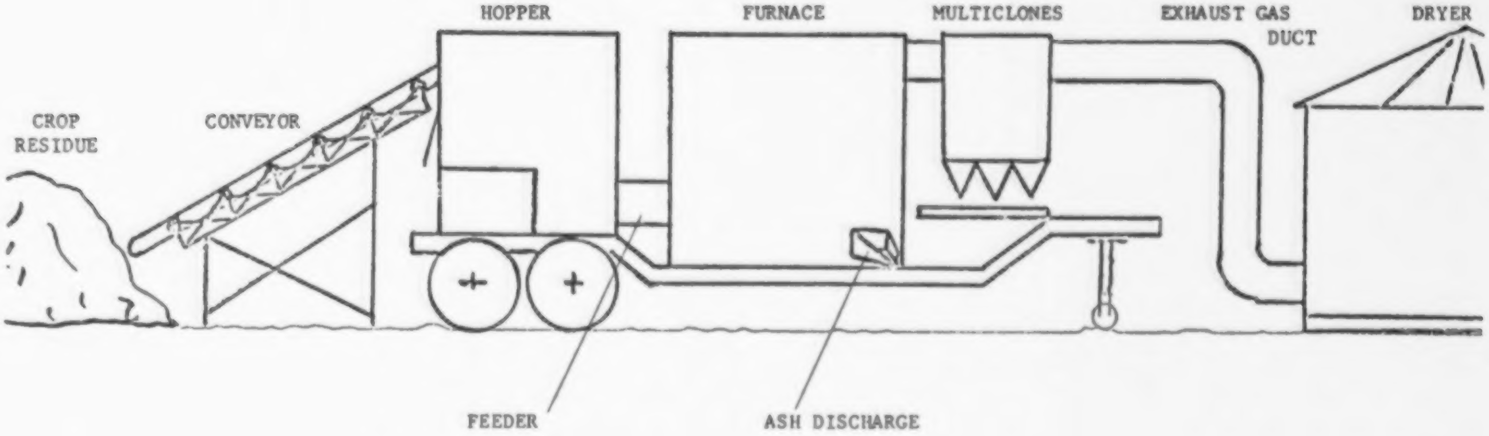

CROP
RESIDUE
CONVEYOR
HOPPER
FURNACE
MULTICLONES
EXHAUST GAS
DUCT
DRYER
FEEDER
ASH DISCHARGE

Figure 60. Schematic of mobile agricultural residue incinerator system.

be determined. An overall energy balance must be performed with consideration given to the incremental energy increase associated with combined harvesting of the residue with the grain and the subsequent handling of the residue.

TABLE 87. FUEL CHARACTERISTIC OF CORN STOVER

Parameter	Weight Percent
Water	25
Ash	3.0
Carbon	30
Sulfur	0.4
Remainder (predominantly hydrogen, oxygen, and nitrogen)	41.6
	100.0

Heating value: 2600 kcal/kg (4675 Btu/lb) (wet basis)

TABLE 88. HEAT BALANCE ON CORN RESIDUE INCINERATOR - DRYER SYSTEM

Basis: 1 kg of corn dried from 25 to 15 percent moisture

Heat In

$$(\text{Heat value of corn residue})\left(\frac{\text{combustion efficiency}}{100}\right) = \text{heat in}$$

$$(2600\ \text{kcal/kg})(.95) = \frac{2470\ \text{kcal}}{\text{kg}}$$

Heat Losses

$$(\text{Heat in})\left(\frac{\text{Percent heat loss}}{100}\right) = \text{heat losses}$$

$$(2470\ \text{kcal/kg})(.25) = 618\ \text{kcal/kg}$$

Heat Available for Drying

$$(\text{Residual heat})\left(\frac{\text{percent drying efficiency}}{100}\right) = \text{heat available}$$

$$(2470\ \text{kcal/kg} - 618\ \text{kcal/kg})(.25) = 460\ \text{kcal/kg}$$

Heat Required for Drying

$$\left(\begin{matrix}\text{Difference in moisture content}\\ \text{of undried and dried corn}\end{matrix}\right)\left(\begin{matrix}\text{Latent heat of vapori-}\\ \text{zation of water}\end{matrix}\right) + \left(\begin{matrix}\text{Sensible heat}\\ \text{increases}\end{matrix}\right) =$$

$$(1.0\ \text{kg})(.10)(550\ \text{kcal/kg}) + 1.0(0.5\ \text{kcal/kg-C})(50\ \text{C}) = 80\ \text{kcal/kg}$$

Net Heat Available

Heat available - heat required = (460 - 80) = 380 kcal/kg

SECTION 7

ENVIRONMENTAL ASSESSMENT

OBJECTIVES OF PRELIMINARY ENVIRONMENTAL ASSESSMENT

The collection and processing of organic matter, together with the conversion of these energy containing substrates, has potentially important environmental impacts. These influences will almost certainly be felt at the local and regional level but, if implemented on a large enough scale, could become national or global issues. In many cases, the utilization of biomass for energy must be considered as an environmentally sound alternative since present resource economics assign very low or negative market values to these wastes. The disposal or recycling of the solid and liquid residues from biomass conversion may also have beneficial aspects when rising petrochemical fertilizer costs increase the attractiveness of these options and land prices for disposal become prohibitive without volume reduction of wastes.

Other biomass feed sources may be part of a complex natural feedback system which provides a replenishment of mineral and organic material to the production system. Unwarranted damages may be inflicted by the improper management of these natural resources.

Little attention has been paid to a comprehensive analysis of the collection and processing techniques for biomass synthetic fuels and the associated effects on the environment. The areas impacted will range from highly natural and unspoiled surroundings whose rhythms should not be upset to densely settled urban areas whose inhabitants justifiably lay claim to clean air and water. Because of the early stage of development of these technologies, information gathering on environmental effects can proceed alongside research on engineering and process variables.

IMPACT ASSOCIATED WITH GROWTH AND PROCUREMENT OF FEEDSTOCK/SOURCE MATERIALS

The range of materials which are amenable to collection and transformation spans the continuum from man generated to plant produced. Each of the source regions presents a unique set of circumstances in terms of the degree and nature of the disturbance. Careful management of the resources contained in residues collected from agricultural and forested lands must be practiced in order to maintain a continuing high level of productivity while providing a useful source of energy. Conversely, conversion of animal manure and municipal wastes entails recognizing that the use of valuable energy resources should not eliminate the need to maintain closed cycles of materials flow to the extent practicable.

Forestry Residues/Silviculture

Discussion of the environmental aspects of silviculture and forestry residues as biomass sources can logically be treated as an entity. The environmental effects of collecting and transporting these materials will be subdivided into those associated with changing land use, alterations of the physical/chemical environment, and alterations in the ecology of impacted forest communities.

Land Use--

The potential land use impacts directly attributable to collection, storage, and preprocessing of forest floor wood residues, mill wastes, and other cellulosic fragments now considered unusable are linked with the developing markets for these materials. Increasing acreage on which residue collection is practiced is also related to the trend toward more intensive silviculture. An estimated two-thirds of the increase in the demand for domestic wood by the year 2000 will be met by use of logging residues(191). Use of wood residues for new wood products will, therefore, compete with the use of residues for fuel.

Indications from the literature are that only a very small portion (< 10 percent) of the total forested area in the U.S. is presently affected by primary residue recovery activity. Primary residue recovery is defined as an attempt to collect and utilize tree tops, small branches and leaves, and stumps. The diffuse nature of this material has made its collection unprofitable. However, the development of new methods of collection which permit the efficient gathering of smaller, more irregular pieces will increase the land impacts substantially. The practice of yarding unused material (Y.U.M.) is a step in this direction. In addition, if the trend toward outdoor recreation continues, negative public reaction to logging slash in clear-cut areas will be magnified and logging concerns will be forced to implement conservation practices on more acreage.

The land area needed for yard storage and drying facilities will increase in direct proportion to the change in usable wood and wood wastes. Actual assessment of the storage and drying needs will best be performed on a regional basis taking into account:

- The daily supply requirements of the generating facility
- The degree of drying which produces optimal operating conditions is related to energy conversion and plant emissions
- Whether gathering operations can proceed during the winter months
- Constraints particular to the drying operation as for example, the maximum dimensions of a drying pile and the drying rate.

Alterations in the Physical/Chemical Environment--

Forest systems generally consist of terrestrial, aquatic and atmospheric components. Each of these is interrelated through the mixed physical and chemical exchanges of materials and energy. If left undisturbed, forests tend to reach an equilibrium which represents the most energetically efficient use of available resources. Each of the components, soil, water, and air, behaves in such a way as to maintain the balance.

Forest soil is classified into three zones or horizons which represent stages in the recycling of vital elements:

1. L - Litter layer consisting of unaltered dead remains of plants and animals.
2. F - Fermentation layer consisting of partly decomposed organic matter. The structure of the plant debris is generally well enough preserved to permit identification of its source.
3. H - Humus layer consisting for the most part of well decomposed, amorphous organic matter(192).

Clearly, the impacts of removal of material from the forest floor will be related to the rate and extent of removal and to the "characteristic patterns of litter fall, humus accumulation, and decomposition occurring in different forest types"(193). Collection of residues leads to departures from the steady-state nutrient and organic matter (OM) cycles typical of a mature ecosystem. The magnitude and rate of the shift toward a smaller nutrient and OM pool is determined by the fraction of new litter which is removed. The percentage of vegetation removed will depend on the particular harvesting practice adopted, e.g., whole tree versus chip collection. The distribution of wood material among the various components of the forest is shown in Table 89.

Loss of organic matter due to harvesting and residue collection occurs in two ways. The primary harvesting effort removes about two-thirds of the organic matter when all residue is collected. The amount of residue generated by cutting operations is highly variable and dependent on technique and equipment employed. Various estimates place the quantity of slash at between 15 and 227 metric tons per hectare (7 to 101 tons per acre)(3,4,5). During revegetation seasonal leaf and dead branch contributions to forest floor litter loads are smaller than they had been in a pre-harvest condition. Until this new growth is established, which may require several years, the organic matter pool is not at a steady-state.

TABLE 89. ESTIMATE OF MATERIAL REMOVAL DUE TO CLEAR CUTTING AND RESIDUE COLLECTION COMPARED TO INSTANTANEOUS POOL SIZE (194)

Parameter	Amount[a] MT/ha	Percent of Total Vegetation
Total tree layer	163	69
Subterranean stems and roots	15	6
Dead vegetation and annual herb and shrub layer	59	25
Total	237	100

(a) Content in each compartment was variable depending on season; oven-dry weight basis

The quantitation of this loss is best performed by simulation modelling of the ecosystem and is beyond the scope of this report.

The removal of organic matter and nutrients by slash harvesting is 20 to 50 percent of that due to bole and branch harvesting(194). This quantity may be important if short period rotation practices are utilized and in fact is four to seven times the annual accumulation of litter reported for white oak in Illinois(197). An extreme example of the detrimental effect of the repeated removal of floor litter showed that in adjacent stands the degradation in soil quality caused a 25 percent reduction in board foot volume per acre when litter was removed(198).

A number of other secondary changes in the physical-chemical systems are induced by cutting and residue recovery. These include:

- Water holding capacity, evaporation, transplantation and runoff

- Soil loss
- Nutrient release rates
- Depth of aeration
- Reflectivity and heat flux.

Differences in infiltration capacity (and, by inference, in runoff) associated with different soil properties have been measured by a number of authors and are listed in Table 90 as simple linear correlation coefficients. When these factors were combined, the highest multiple coefficient was obtained with noncapillary porosity and organic matter in both surface and subsoil(197). The effect of removal of the top 7.5 cm of forest floor organic matter in a Colorado pine stand was to decrease the average infiltration rate by 40 percent which was highly significant statistically(199). Reduced infiltration coupled with higher overland sheet flow velocities caused severe sheet and rill erosion, increased loading of nutrients to nearby waterways, and reduced dry weather soil moisture.

TABLE 90. CORRELATION BETWEEN FOREST SOIL PARAMETERS AND INFILTRATION RATE

Parameter	r
Noncapillary porosity, subsoil	0.54
Organic matter, surface	0.50
Clay content, subsoil	-0.42
Organic matter, subsoil	0.40
Noncapillary porosity, surface	0.36
Total porosity, subsoil	0.36
Volume weight, subsoil	-0.33
Aggregation, surface	0.30
Moisture equivalent, subsoil	-0.30
Suspension, surface	-0.29
Total porosity, surface	0.24
Silt + clay, subsoil	-0.24
Volume weight, surface	-0.24

The influence of vegetal density on erosion rates can be best illustrated by pointing out that the material transport ability of moving water varies as the velocity to the fifth power(200) so that erosive soil losses may be substantially increased for small increments in water velocity.

The most comprehensive study located of particulate export from forested ecosystems is that conducted on the Hubbard Brook System, New York, by Borman et al(201). The findings were generally consistent with expectations based on theoretical considerations. As stated in the results, deforestation had a pronounced effect on the amount and size of particulate matter exported, the proportion of organic to inorganic material, and the origin of organic matter.

In terms of erodibility, the mature forested ecosystem had an output of 25.4 kg/ha (total particulate matter) versus 156.0 kg/ha for the clear-cut plots (22.7 lbs/acre versus 139.2 lb/acre). Short, intense rain events were cited as being most responsible for the differences. In addition, the deforested systems tended to export a larger fraction of inorganic materials. However, these relationships may be altered somewhat if revegetation is allowed to proceed at the natural rate instead of being suppressed as it was in this study. Finally, the major contribution to organic material export differed for the two treatments. In the steady-state, mature area, newly fallen litter was inconsequential as a source of export of organic matter with the major supply derived from streambed deposits. The opposite was true for the cut-over areas.

The implications of intensive silviculture and slash collection for water quality relate to the increased transport of detached soil particles, organic materials, and associated chemical species to nearby lakes and streams. Most of the principal factors controlling changes in water quality have been discussed previously. The yield of particulates, soil material and organic debris is determined in part by the distance to water and in part by topographic and hydrologic characteristics of an area. One other consideration is the selection of logging and slash recovery systems. Effects range from severe to superficial, depending on methods used and degree of planning(202). Various methods have been developed to quantify the loss of soil from various land parcels. Wooldridge(203) has used mean water-stable aggregate size as a measure of erosion hazard. One of the most widely used techniques for erosion estimation is the Universal Soil Loss Equation developed by Wischmeier and Smith(204,205) and Wischmeier(206) and widely used by the Soil Conservation Service of the USDA. It empirically predicts gross sediment transport from small watersheds as a function of soil type, degree of vegetative cover, and topography. Table 91 presents cover factors for use of this equation. The accuracy of estimation declines as the drainage basin area increases unless additional factors are introduced. Generally, the higher the organic matter content, the larger the aggregate, and the less erodible the soil(207). Increased losses of nutrients and other elements as a result of forest floor and canopy disturbance seem to be universal. Both surface and ground water are likely to be affected. Increased levels of nitrates are a cause for concern where

TABLE 91. COVER FACTORS FOR WOODLAND USED IN THE UNIVERSAL SOIL LOSS EQUATION

Condition	Tree Canopy[a] % of Area	Forest Litter[b] % of Area	Undergrowth[c]	Cover Factor
Well stocked	100-75	100-90	Managed[d]	0.001
			Unmanaged[d]	0.003-0.011
Medium stocked	75-40	90-75	Managed	0.002-0.004
			Unmanaged	0.01 -0.04
Poorly stocked	40-20	70-40	Managed	0.003-0.009
			Unmanaged	0.02 -0.09

[a] When tree canopy is less than 20% the area will be considered as grassland or cropland for estimating soil loss.

[b] Forest litter is assumed to be at least 5 cm (2 in.) deep over the percent ground surface area covered.

[c] Undergrowth is defined as shrubs, weeds, grasses, vines, etc., on the surface area not protected by forest litter. Usually found under canopy openings.

[d] Managed--grazing and fires are controlled; unmanaged--stands that are overgrazed or subjected to repeated burning.

Reference: Wischmeier (208).

water is used for drinking purposes downstream or downgradient. Since undisturbed forest systems cycle nutrients vary efficiently, a disturbance which creates additional runoff usually raises the primary productivity of the aqueous system if nutritive factors were limiting.

Export of nutrients, as well as other elements, was monitored during the Hubbard Brook investigation and reported in several articles.(193,201,208) Gosz, et al(193), determined that removal of elements by leaching was proportional to the water-soluble organic content. Total nutrient loss was determined to be a function of vegetation type, extent and nature of the cut, slopes, and drainage patterns.

Deforestation had marked effects on loss of all elements measured with the exception of sulfur. Elements were grouped according to the severity of the increase in loss rates:

< 10 times	N,P,K
5-9 times	Al,Ca,Fe
> 4 times	Cl,Si,Na.

It should be noted that the elements shown to suffer the greatest losses are those required by plants in the largest amounts. The most immediate response of the system was the increased solubility of nutrients. Because of the increased rate of organic matter decomposition and increased nitrification, nitrogen was rapidly removed from the system. An estimated 1.5 to 2.5 times the annual uptake was lost as dissolved nitrogen mainly in the form of nitrates. The hydrogen ions from bacterially mediated nitrification released nitrates according to the equation:

$$NH_3 + 2O_2 \longrightarrow NO_3^- + H^+ + H_2O \ .$$

The hydrogen ions tend to compete with and displace other cations, most importantly calcium, from the exchange sites in the soil. Also, the excess proton activity acts to lower the soil solution pH affecting solubilities of various elements. The general conclusion reached by the authors was that while element cycling within the ecosystem is temporarily "loosened", the natural equilibrium soon reasserts itself to minimize adverse impacts.

Two other effects of canopy and residue removal should be mentioned although their consequences can be minimized by proper management. Research indicates that changes in percent canopy cover and the removal of forest floor affect soil temperatures. Toumey and Neethling(209) state that temperatures in the shade are as much as 17 C cooler than in sunny areas where floor material (12.7 cm) is allowed to remain and 22 C cooler than where both canopy and floor are removed. Higher soil temperatures accelerate biological processes and may lead to stress on the decomposer population.

Compaction of soil by harvesting/collecting equipment and reduced infiltration caused by vegetation removal usually has pronounced effects on the magnitude of flood flows. In a comparative study on forested and deforested water sheds in Colorado, the beginning of the rise in the hydrograph was 12 days earlier, the dates of the flood crests were 3 days earlier and the crests averaged 69 percent higher in the deforested basin(210).

The air-related impacts of slash harvesting include the changes in emission of hydrocarbons and oxides of nitrogen. Acceptance of the definition of an atmospheric pollutant as a substance present in sufficient quantities near enough to people, plants or animals to produce deleterious effects demands the consideration of forest residue burning as a serious pollutant. The area of slash created and the treatment merits mention, although national data are not available (Table 92). Use of wood wastes for fuel will partially alleviate the need for burn-over and the attendant particulate and gaseous emissions. Offsetting this benefit to some degree will be the increased emissions from internal combustion engines used in slash recovery unless efforts are made to advance logging/harvesting technology to the point where residues are collected simultaneously with the primary harvest.

Ecological Impacts--

Removal of vegetation from the forest floor will cause changes in most of the trophic levels associated with the decomposers. However, the rate of decomposition is dependent on the mass and size distribution and the composition of decomposable litter.(211) Nutrient content varies with differences in tree species and is higher in the foliage component. Foliage, twigs, and small branches are readily

TABLE 92. CHANGES IN ACREAGE OF SLASH CREATED AND SLASH TREATMENT ON FORESTS OF THE PACIFIC NORTHWEST REGION (256)

Method	-10^3 Acres-	
	1963	1972
Clearcut	57	63
Partial cut	284	549
Broadcast burn	45	26
Pile and burn	0	87
Receiving extra protection:		
Clearcut	0	36
Partial cut	512	912

assimilated and contribute the major portion of microbial nutrients while accounting for only a minor fraction of the total residue volume. Other environmental niches which may be affected by residue and canopy removal are those supplying forage and cover to small animals.

Transport of organic materials and sediments to streams causes changes in productivity and species diversity. Depending on the previous water quality history of the stream, higher suspended solids concentrations (reduced light penetration) may decrease primary productivity or cause a shift to more shade tolerant aquatic species with a resulting lower species diversity index (SDI). On the other hand, the enrichment potential of an increased nutrient load may increase the net rate of carbon fixation, associated with increased rooted aquatic plant and algae growth, while still causing a reduced SDI due to the exclusion of less tolerant forms. Increased BOD and sediment loads also cause stress on the fish and benthic communities. Changes in peak storm flows and subsequent scouring effects on stream banks and bottom may disturb spawning grounds and destroy niche areas of bottom dwellers. In backwater pool areas, drops in dissolved oxygen levels due to organic decomposition may favor anaerobic fauna, if low-flow conditions persist for long periods.

On the positive side, it has been claimed that large volumes of debris depress forage production and increase the potential for fire and that some type of treatment to reduce, but not eliminate, this volume would produce desirable and beneficial ecological effects(212). High intensity fires occur with heavy accumulations of fuel and are difficult to control(212). Quantity reduction, then, may offer a reduced hazard potential. Quantity alone, however, does not indicate what fuel is available for combustion. Fuel availability depends on moisture content, size of material, and the ratio of living to dead combustible material.

Summary -- The literature on the inventory and estimation of environmental impacts of silviculture and residue recovery for energy production indicates a paucity of quantitative investigations. Where these have been conducted, as in the case of the Hubbard Brook study, the experimental treatment seems to be conceived of as a "worst case" situation. Since the degree of ecosystem disturbance owing to harvesting, removing, and storage of forest materials is a continuum which depends on many regional, site, and engineering variables, it would seem appropriate to examine other points along the continuum. In general, the transformations indicated by Figure 61 should be examined in greater detail for their response to differing degrees of harvest/recovery activity. The manner in which the terrestrial, aquatic, atmospheric, and biological components interact and respond to a severe perturbation is shown in Figure 61, excerpted from the Hubbard Brook study. In general, the transformations are expected to be qualitatively similar for all forest systems, but the magnitude of impact will be contingent upon the degree of harvesting/recovery activity. Reductions of organic matter in some regions may provide several benefits. Research is needed to predict the amount of removal that can take place on a continuous basis.

It should be emphasized further that many of the potentially adverse impacts can be mitigated by utilization of available erosion control technology and engineering judgement. These measures might include stand selection and harvesting techniques which minimize soil disturbance, development of an adherence to specified guidelines, establishment of buffer zones around environmentally or aesthetically sensitive areas and so forth. Silviculture has also been tried successfully on marginal strip-mined land in the hopes of restoring some degree of productivity. Thus the net impact may be positive.

Agricultural Crop Residues/Energy Crops

Methods of collection and conversion of energy crops to fuels are similar to those used in the conversion of agricultural residues. Therefore, the environmental effects of the conversion of both biomass sources will be discussed in this section. Since the basis for discussion presupposes commitment to crop production, land use will not be discussed. The ecological effects will be similar in many aspects to those discussed in the section Forestry Residues/Silviculture and will not be repeated.

·Alterations in the Physical/Chemical Environment--

Environmental responses to the collection and use of crop wastes and harvesting of energy crops are qualitatively similar to those from forest residue/silviculture. Keeping in mind that the time frame is much shorter for crop residues and energy crops (1 year versus 2-15 years for intensive short-rotation forestry), many of the highlights present in Section 3.1.1 are applicable.

The major alterations to be evaluated regarding intensified crop waste collection or energy crop production are:

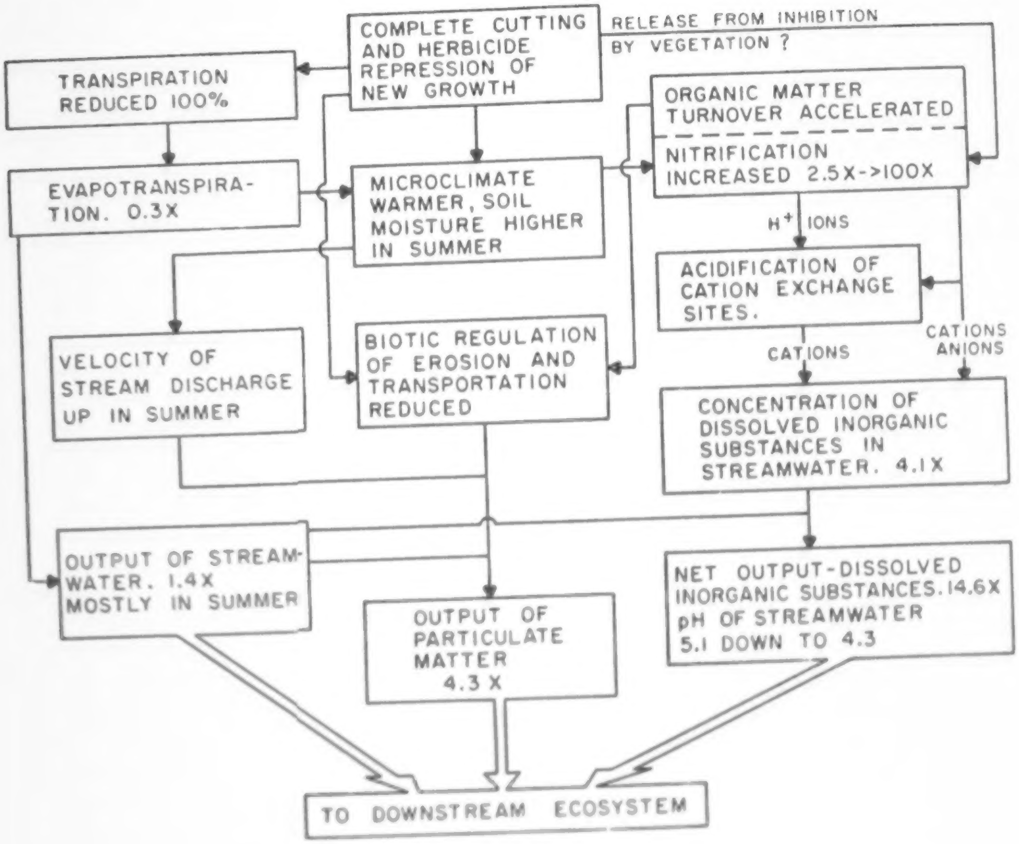

COMPLETE CUTTING AND HERBICIDE REPRESSION OF NEW GROWTH
RELEASE FROM INHIBITION BY VEGETATION ?
TRANSPIRATION REDUCED 100%
ORGANIC MATTER TURNOVER ACCELERATED
NITRIFICATION INCREASED 2.5X->100X
EVAPOTRANSPIRATION. 0.3X
MICROCLIMATE WARMER, SOIL MOISTURE HIGHER IN SUMMER
H+ IONS
ACIDIFICATION OF CATION EXCHANGE SITES.
VELOCITY OF STREAM DISCHARGE UP IN SUMMER
BIOTIC REGULATION OF EROSION AND TRANSPORTATION REDUCED
CATIONS
CATIONS ANIONS
CONCENTRATION OF DISSOLVED INORGANIC SUBSTANCES IN STREAMWATER. 4.1X
OUTPUT OF STREAMWATER. 1.4X MOSTLY IN SUMMER
OUTPUT OF PARTICULATE MATTER 4.3 X
NET OUTPUT-DISSOLVED INORGANIC SUBSTANCES. 14.6X pH OF STREAMWATER 5.1 DOWN TO 4.3
TO DOWNSTREAM ECOSYSTEM

Figure 61. Effect of clearcutting on hydrology and materials cycling.(201)

- Increased usage of inorganic or organic (animal manure) fertilizers
- Changes in the amount of sediment transported by runoff
- Alterations in normal nutrient cycles
- Variations induced in soils-texture, organic matter, water holding capacity, and mineral content.

The objective of soil management is the maintenance of near steady-state conditions. Ideally, applications of fertilizers and mulch/organic material should just match the deficits created by harvesting of the crop because over-fertilization results in excessive nutrient runoff losses and under-fertilization reduces yields. This statement is never totally true in practice because of time-varying influences in nutrient availability and crop needs. However, for present purposes the implications of the information in Table 93, an assessment of nutrient removal when harvesting for conversion, are that about 35-40 percent of the annual needs of the plant crop would be removed each year in harvesting the stalks and leaves. This imbalance would be correctable in a number of ways:

- Drawing on soil reserves to increase supply, e.g., increased solubility of phosphorus due to greater concentration gradient
- Higher application rates of commercial fertilizers
- Use of supplemental fertilizers such as manure and/or sludge.

Harvesting an energy crop such as sugar cane would, of course, remove nearly 100 percent of the annual uptake.

Traditional soil management techniques preserve soil integrity through additions of inorganic fertilizers, erosion reduction and plow-under of crop residue. Recently, due to increased costs of fertilizers, many farms have begun augmenting super phosphate and anhydrous ammonia treatments with mulch derived from animal manure, secondary treated effluent or sludge. The primary benefit of such practices (manure spreading or plow-down) is the increased organic matter content carried over to the following growing season, although some nutritional requirements of the crop may be satisfied in this manner. There have been some suggestions to utilize animal manure and solid waste for energy production. Depending on the demand and supply conditions, use of these materials as soil amendments may be severely curtailed thus placing greater importance on soil conservation practices and recycling of organic materials in stubble. Stubble left in the field aids in erosion resistance by reducing the kinetic energy of raindrop impact, slowing the sheet velocity of overland flow, increasing tilth, and improving soil agglomeration by increasing chemical and mechanical binding.

A number of methodologies for estimating erosive soil loss and nutrient transport have been developed ranging from highly generalized empirical estimators such as the Universal Soil Loss Equation (USLE) to highly sophisticated computer-based simulation models which incorporate detailed

TABLE 93. AMOUNTS OF MAJOR NUTRIENTS REMOVED BY CORN RESIDUE COLLECTION FOR USE AS A FUEL SOURCE (a)

Parameter	Annual Uptake (kg/ha-yr)(b)	Percent of Dry Weight (mean)(c)	Amt. Removed (kg/ha-yr)	Percent of Total Annual Uptake Removed(d)
P	32	0.15	11.3	35.3
N	168	0.91	68.4	40.7
K	158	0.74	55.6	35.2
Ca	-	0.32	24.1	-
Mg	-	0.24	18.0	-

(a) Assumes 100 percent residue collection efficiency.

(b) Yield 120 bu/ac (297 bu/ha). Keeney, D. R., et al.(213).

(c) Gerloff, G. C.(214).

(d) Assuming 5600 lb (2500 kg) residue per bushel (7.52 MT/ha for 297 bu/ha yield)(215). Does not include below-ground portion of plant mass or nutrients.

soil moisture accounting and chemical kinetic parameters. Because of the diversity of agricultural management practices available, it would be futile to generalize regarding the amount of change in soil or nutrient loss to be expected with continuous removal of stubble. For example, on conventionally tilled (continuous, row-planted) corn, average annual soil loss is increased by approximately 24 percent if residue is removed. However, if a winter cover crop is seeded and plowed under, soil loss is decreased by 5 percent, even though residue is still removed. Also residue removal may be only partial, that is, root material may be allowed to remain so that soil retention ability is not completely lost.

Long-term continuous removals of residue and/or high yield production would produce unacceptably high erosion rates under most slope and soil conditions.

The USLE is:(208)

$$A = RKLSCP \quad \text{where}$$

A = Average annual soil loss per unit area

R = Rainfall factor (accounts for both the duration and intensity of a rain event by specifying the number of erosive index units accumulated per year). The erosive index unit is a measure of the erosive force of a specified rainfall.

K = Soil erodibility factor

L = Slope length in feet

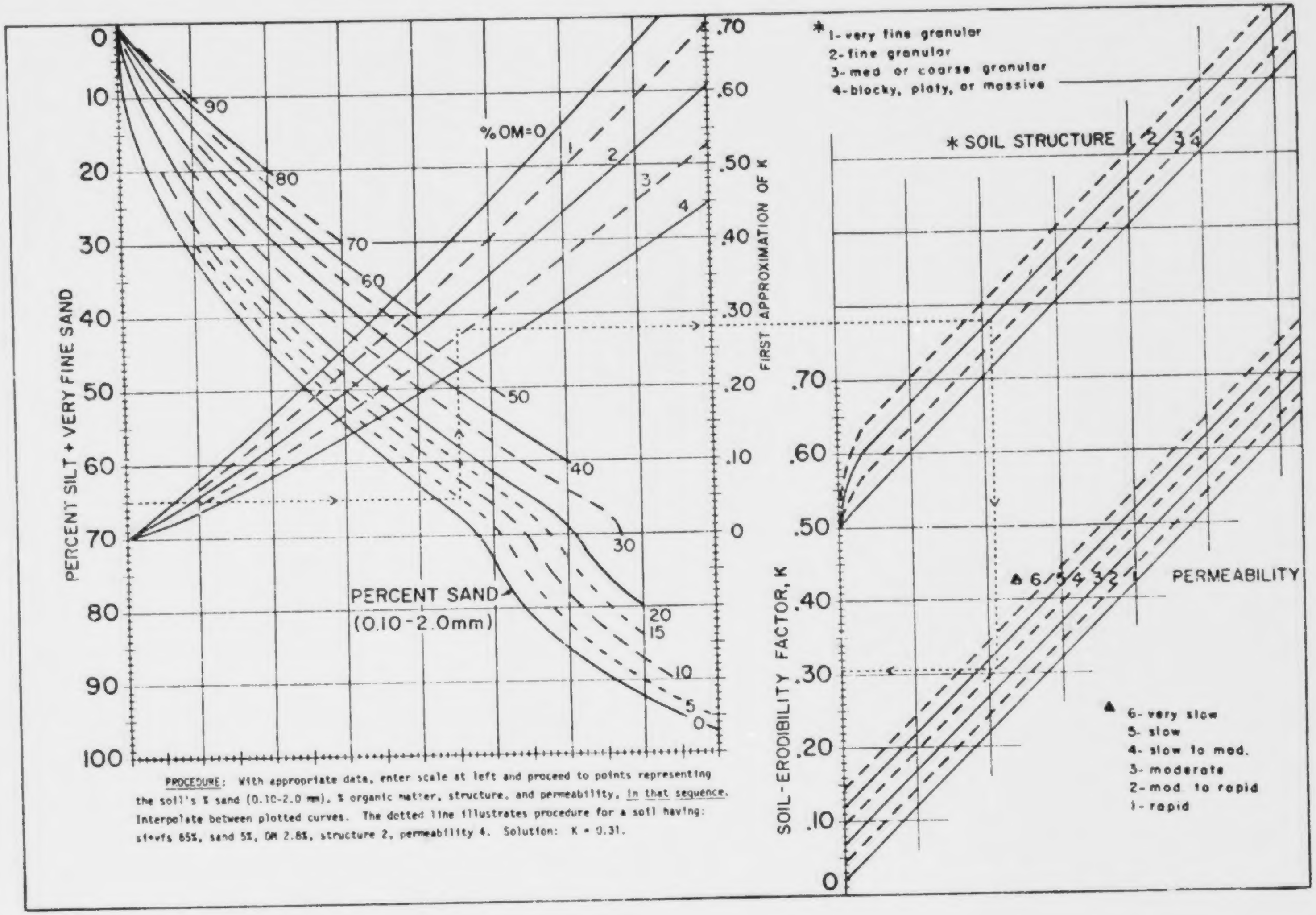
S = Degree of slope

C = Cropping management factor - permanent vegetation < grass meadow - legumes - small grains - row crops - fallow = 1.0

P = Cropping practice factor - contour tillage, strip-cropping, etc.

The contribution of organic matter content, both directly and indirectly, to the erodibility factor, K is shown in Figure 62. Besides the direct effects, low organic matter (PM) content produces tightly structured, low permeability soils.

Water quality impacts under high productivity, poor management conditions would be similar to those encountered under the "worst case" silviculture/forest residue situation. Forest soils may have higher K values on the average than soils suited for agriculture. If proper management is neglected, heavy siltation and nutrient runoff will result. This will be an especially severe problem on lands marginally suited for crop production. Other water quality influences result from storage/drying of bagasse and stubble. These areas must be protected from rainfall/runoff because of the potential leaching and transport of BOD, nutrients, and solids to streams and lakes. These pollutant sources are similar in some ways to those generated from storage of animal wastes and may, in extreme cases, need to be treated as such.



PROCEDURE: With appropriate data, enter scale at left and proceed to points representing the soil's % sand (0.10-2.0 mm), % organic matter, structure, and permeability, in that sequence. Interpolate between plotted curves. The dotted line illustrates procedure for a soil having: si+vfs 65%, sand 5%, OM 2.8%, structure 2, permeability 4. Solution: K = 0.31.

Figure 62. Relationship between soil erodibility and physical-chemical composition.

Atmospheric effects would include changes in reflectivity as a result of longer periods of dark soil surface exposure and greater amounts of airborne dust due to wind erosion.

Summary--

The practice of removal of crop residues such as corn stalks or the harvesting of energy crops has two major potential impacts - the loss of nutrients and organic matter associated with continued withdrawals of biomass and the increased erodibility of exposed soils, especially in northern climes where spring snow melt-runoff occurs. Judging from previous research on environmental effects associated with intensive agricultural production, both of these limitations can be minimized. Methodologies for minimizing erosion and nutrient loss will have to be utilized. These might include terraces, contour cropping, fertilizer plow-down with controlled application timing, and rotations which would permit only a limited number of energy/residue crops. With good planning, adverse impacts should be at or below those from traditional agriculture. Also, if a biochemical conversion process, such as anaerobic fermentation, is utilized, much of the original chemical content of the stubble remains and could be recycled back to the land.

Animal Waste

Physical/Chemical Impacts--

Animal production facilities can be broadly classified as small, individually-owned farms or large commercial operations. Animal waste collection for biomass conversion is a more likely alternative on the large feedlots for economic reasons. Therefore, the analysis will be largely confined to these. Manure is presently stacked and allowed to ferment due to a lack of utilization alternatives. In some instances, it is treated further in anaerobic or aerobic lagoons to reduce pollutional loadings to ponds and streams or is spread on agricultural land.

Land-spreading of raw or treated manure has both positive and negative aspects. Application of manure at 33.6 MT/ha (15 T/ac) on continuously cropped corn land decreased surface run-off by 16 to 24 percent(217). A 605 MT/ha (270 T/ac) loading rate with wet cattle manure reportedly increased the field moisture capacity 12 percent(217). Soil structure is also improved by additions of manure. The potential pollution problems associated with the handling and disposal alternatives for animal waste have been addressed in detail in the literature (Tables 94 and 95). Briefly, these include:

- Phosphorous and nitrogen loading to surface waters are increased; especially when improper management practices are adopted
- BOD loads are also often increased
- Odor problems sometimes create nuisances
- Nitrate contamination of ground water may occur
- Storage of large quantities of high moisture manure induces vector production and may indirectly lead to runoff of biocides used to control the pests.

TABLE 94. RANGE OF OBSERVED VALUES IN CONCENTRATION AND AREA YIELD FOR VARIOUS LAND USES(218)

Source	Concentration (mg/l) COD	BOD	NO_3-N	Total N	Total P	Area yield rate (kg/ha/year) COD	BOD	NO_3-N	Total N	Total P	Surface area of interest
Precipitation	9-16	12-13	0.14-1.1	1.2-1.3	0.02-0.04	124	—	1.5-4.1	5.6-10	0.05-0.06	Total land area
Forested land		—	0.1-1.3	0.3-1.8	0.01-0.11	—	—	0.7-8.8	3-13	0.03-0.9	Forest area
Range land		—	—	—	—	—	—	0.7	—	0.08	Range land
Agricultural crop land	80	7	0.4	9	0.02-1.7	—	—		0.1-13	0.06-2.9	Active crop land
Land receiving manure	—		—	—	—	—	—	—	4-13	0.8-2.9	Crop or unused land used for manure disposal
Irrigation tile drainage, western United States											
Surface flow	—	—	0.4-1.5	0.6-2.2	0.2-0.4	—	—	—	3-27	1.0-4.4	Irrigated western soils
Subsurface drainage	—	—	1.8-19	2.1-19	0.1-0.3	—	—	83	42-186	3-10	Irrigated western soils
Crop land tile drainage	—	—	—	10-25	0.02-0.7	—	—	—	0.3-13	0.01-0.3	Active crop land requiring drainage
Urban land drainage	85-110	12-160	—	3	0.2-1.1	220-310	30-50	—	7-9	1.1-5.6	Urban land areas
Seepage from stacked manure	25,900-31,500	10,300-13,800	—	1,800-2,350	190-280	—	—	—	—	—	Manure holding area
Feedlot runoff	3,100-41,000	1,000-11,000	10-23	920-2,100	290-360	7,200	1,560	—	100-1,600	10-620	Confined, unenclosed animal holding areas

[a] Data do not reflect the extreme ranges caused by improper waste management or extreme storm conditions; the data represent the range of average values reported in previous tables.

TABLE 95. CHARACTERISTICS OF SEEPAGE FROM STACKED DAIRY CATTLE MANURE AND BEDDING(218)

Parameter	Winter		Summer	
	Average	Range	Average	Range
Total solids (%)	2.8	1.8-4.3	2.3	1.7-2.9
Volatile solids (% TS)	55	52-59	53	50-58
Suspended solids (%)	0.35	0.2-0.8	0.24	0.2-0.3
BOD (mg/ℓ)	13,800	4,200-31,000	10,300	4,400-21,700
COD (mg/ℓ)	31,500	21,000-41,000	25,900	16,400-33,300
Total N (mg/ℓ as N)	2,350	1,500-2,900	1,800	1,200-2,770
NH_3-N (mg/ℓ)	1,600	980-1,980	1,330	780-2,200
Total P (mg/ℓ as P)	280	64-560	190	90-340
Potassium (mg/ℓ as K)	4,700	3,000-72,00	3,900	3,000-4,900
Total precipitation (inches)		15.0		9.4
Seepage volume (gal/cow/day)		3.0		1.2

The re-routing of manure to conversion facilities is only feasible if these are located near the feedlot. In some cases this permits the recycling of the spent materials back to nearby agricultural lands. The net loss of the soil conditioners and plant nutrients depends on both the mode of conversion and on the length of storage.

If thermochemical conversion processes such as incineration or mixed refuse feed are chosen, then the options for recycling are limited. Chemical analyses of the residue (char or ash) indicates adequate concentrations of phosphorus and potassium, but less than trace amounts of nitrogen. By itself this provides insufficient economic incentive or crop value. However, if the char were mixed with a material high in organic carbon, it might prove useful as a low-grade fertilizer.

On the other hand, the high moisture content favors the implementation of a fermentation type conversion system. The fact that fresh manure produces much higher quantities of methane is also favorable from an environmental standpoint for several reasons. First of all, the storage requirements may be reduced to some degree. Storage facilities presently employed are less than ideal in many cases. Although the rate of oxygen demand for animal manure is lower than that for secondary treated wastewater effluent, the ultimate BOD is considerably higher by factors ranging from 5 to 167(219,220). Immediate utilization and decomposition of manure in a closed reactor would reduce the BOD problem but would not eliminate it because some liquid residue would still need to be treated. However, the source would be centralized and it might be economically feasible to biologically treat or apply the liquid waste stream to land (see the Section: Impacts Associated with Growth and Procurement of Feedstock/Source Materials). Anaerobic degradation produces a solid residue in which a large fraction of the original weight is retained as a humus-like material ideal as a soil amendment and a liquid by-product high in nitrogen(221).

Small differences in crop yield and nutrient recoveries were noted by Hensler et al(217) with fresh, fermented, and anaerobically digested liquid manure applied to corn fields. The diversion of animal manure to anaerobic digestion plants may have advantages relative to two other aspects of manure management, namely changes in soil chemistry and odor production as a result of application of manure on land. In fact, one of the foremost problems in land disposal of livestock wastes is odor emission(222,223). A wide variety of compounds including volatile organic acids, mercaptans, sulfides, and ammonia contribute to the problem and some or all could be controlled at a central biomass conversion plant(224).

A study conducted by Hileman(225) demonstrated that changes in the physical and chemical qualities of the soil resulted from subsurface chicken manure application.

- The soil pH increases as the equilibria between the ammonia and soil pore water become established

$$NH_3 + H_2O \rightleftharpoons NH_4OH$$
$$NH_4OH \rightleftharpoons NH_4^+ + OH^-$$

- The ammonium cation has a strong affinity for the exchange sites on the soil clay/organic matter complex, releasing Ca, Mg and K.

It was not stated whether these changes were persistent enough to affect crop production. However, chicken manure conversion characteristics are substantially different than those from cattle, as are inherent nutrient content. Since chicken manure is not a major biomass source, it will not be commented on further.

The anaerobic fermentation process alters the pH and converts ammonia into bacterial protoplasm. Thus, the recycled residue is more stable than the feedstock. If this material is then applied to land, the runoff pollution potential with regard to BOD and nitrogen should be low, especially when plowed-under. Nitrate pollution should also be reduced if the time rate of release of nitrogen is lower in the digested material.

In many areas, it is necessary to observe a "resting" or nonapplication period to avoid overloading the soil. The soil surface must be permitted to drain periodically and the pore spaces permitted to fill with air. This is important not only for adequate root growth of crops but for the use of the soil as disposal medium. Compaction impedes root growth, impairs crop productivity, lowers the percolation capacity of the soil, and results in more rapid soil saturation and water loss by runoff. The use of land as a waste water disposal site is practical on a continuing basis only if the application rate is less than the soil infiltration rate. Because the volume of manure generated is often greater than the soil assimilative capacity the tendency is to exceed appropriate levels. Production of methane and recycling of the solid wastes offers the possibility of increased soil loading rates with lower pollution potential.

Summary--

The expected environmental impacts from diversion of animal manure to biomass conversion plants are essentially positive. The pollutant runoff from manure left to lie in feedlots or applied improperly to agricultural land has been identified as a serious concern, to the extent that the U.S. EPA has promulgated effluent guidelines. The generation of usable energy from this source apparently stabilizes the material, reduces the possibility of adverse changes in soil chemistry or structure, mitigates the malodors associated with on-site treatment, and should decrease the production of flies and other pests since storage periods are shorter. The anticipated benefits of using animal manure as a biomass source with regard to environmental pollutants are indicated in Figure 63. A potential disadvantage is that the volume reduction due to digestion may increase the concentrations of heavy metals, but no investigations to verify this could be located.

Aquaculture

Introduction--

In developing a discussion of aquaculture, two species have been selected as representative of the class. Giant kelp has been proposed most

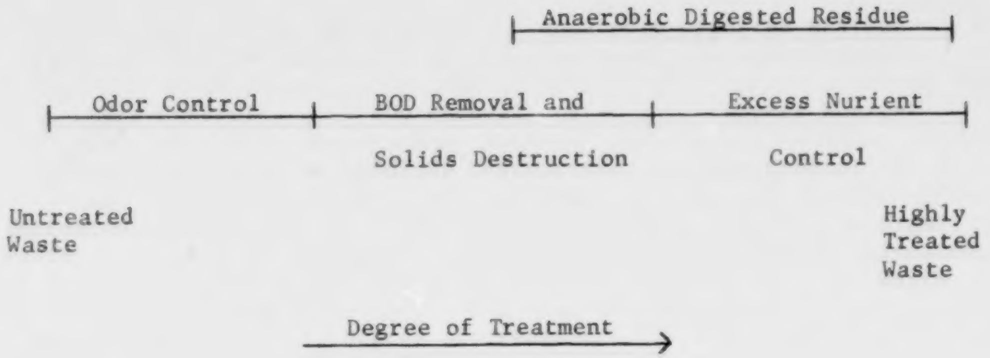


Figure 63. Treatment continuum and expected range of treatment using anaerobic digestion for gas production and recycling residue.(218)

vigorously for marine systems, while water hyacinths have received considerable attention as a fresh water source for simultaneous sewage treatment and energy production.

The oceans represent a vast potential resource above their ability to produce high-quality protein for human consumption. Certain areas have been proposed for transformation into oceanic biomass "farms" if deficiencies in the nutrient levels are corrected and if precautions are taken to protect the marine ecosystem. Giant kelp (Macrocystis) is one species of plant proposed. Interactions may be classified as positive/synergistic, neutral/non-existent, or negative/antagonistic. If the response of the rest of the system are shown to be essentially negative, then some rethinking of the needs and goals of this biomass source seems in order. Some of the same considerations apply to production of biomass from water hyacinths in "closed" fresh water pond environments, albeit on a much reduced size and risk scale.

System Nutrient Requirements and Alterations of the Physical/Chemical/Biological Environment--

The seeding, growth, and harvesting of kelp beds places demands on assimilation and nutrient cycling mechanisms in the ocean. A feasibility study of an ocean farming system in several variations has been conducted by Szetela, et al(226). They attempted to determine the nutrition requirements for maximum growth under available light conditions. However, some of the assumptions in the determination appear unreasonable in the light of known aspects of phytoplankton physiology. In order to calculate the availability of nutrients from dry weight measurements, the assumptions that there would be no competition for nutrients and that the kelp could utilize 100 percent of the available nutrient were necessary. Both assumptions seem to be gross simplifications of the complexities of nutrient cycling in thermodynamically open systems. Although the density of phytoplankton in the ocean as a whole is very low, the areas suggested as good places for mariculture are shallow (< 30 m), well lit, and reasonably high in naturally supplied nutrients. In other words, these areas not only are attractive for kelp production, but also are conducive to the development of other ecological communities. In fact, the western continental shelf area is rated as moderate to high (25-50 mg/m^3-yr) in terms of volumetric productivity while the Gulf Coast is somewhat lower (10-25 mg/m^3-yr) as seen in Figure 64. The western continental shelf already supports a considerable growth of Macrocystis (Figure 65). This area however, appears small relative to that expected for an ocean energy farm. No significant beds occur off the southern Gulf coast.

The seeding and growth of kelp may alter productivity/nutrient patterns in several ways:

- The kelp provides a substrate for the production of epiphytic algae and bacteria. Nutrient estimates (in terms of fertilization requirements) should be re-evaluated considering this additional drain on the system.
- The addition of ammonia may stimulate growth of planktonic algae because the assumption of non-competition seems unwarranted by the results of research on algal physiology.
- The large increase in organic matter production may impact on other ecosystem components because of the excretion of external metabolites as dissolved organic matter (DOM) (Figure 66). These metabolites may be directly used by bacterial populations(228), multicellular algae(229), and by some invertebrates.(230)
- The rain of organic detritus would likely increase in intensity due to segments of stipes and blades breaking off and sinking as a result of wave action. Depending on ambient bottom conditions such as temperature, composition, and currents, the sediment chemistry and benthic organisms may be affected by the decomposition of this material.
- It has been suggested that 25 percent of the nutrient requirements could be met by recycling the residue from the digester(226) in a near-shore environment. If this option proves attractive, the impact of this fertilizer on other system components should be evaluated. It may contain by-products toxic to certain aquatic species or may chelate trace metals forming soluble complexes which are harmful.

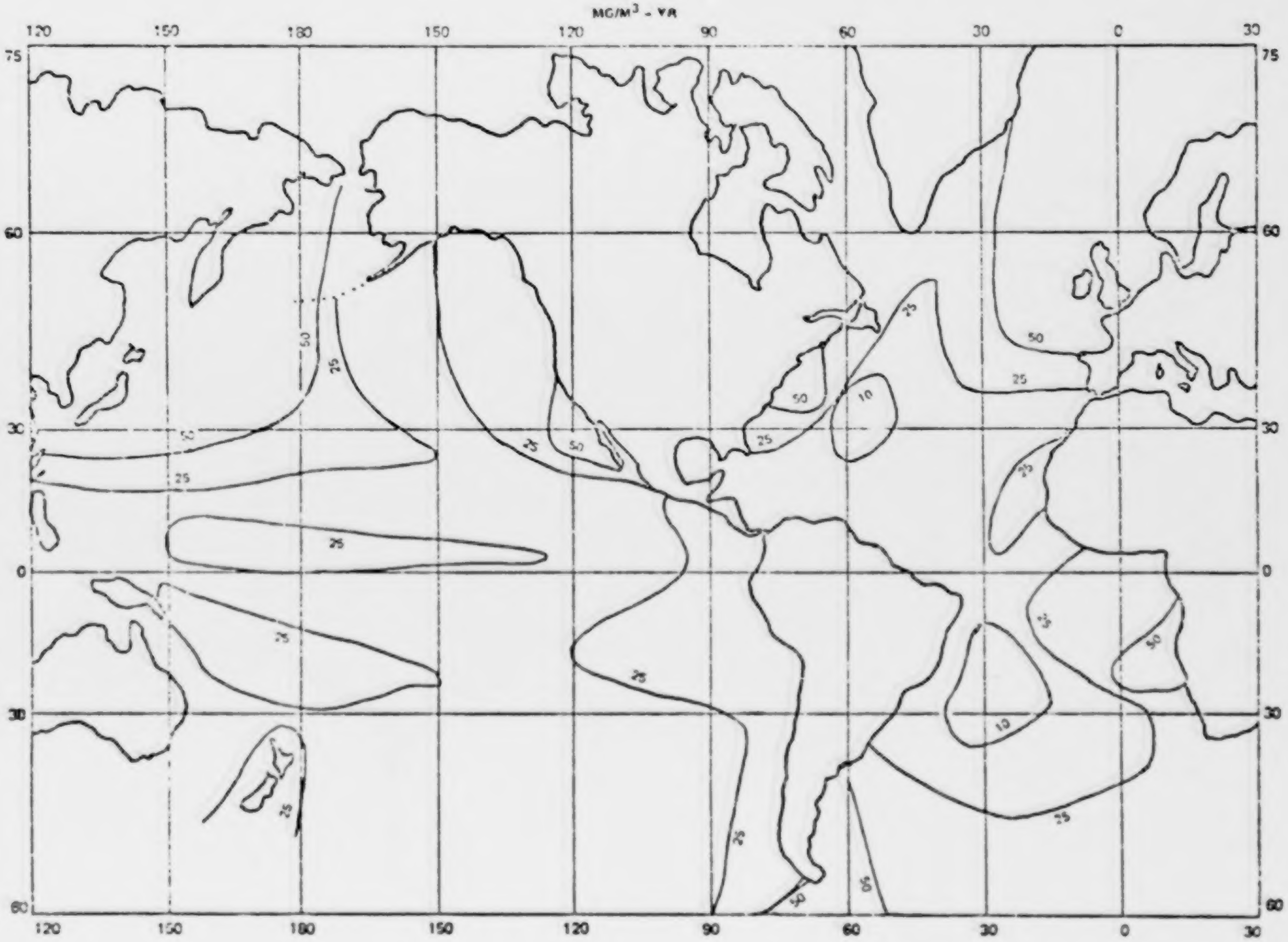

MG/M³ - YR
120
150
180
150
120
90
60
30
0
30
75
60
30
0
30
60
10
25
50

Figure 64. Global production of organic matter.(226)

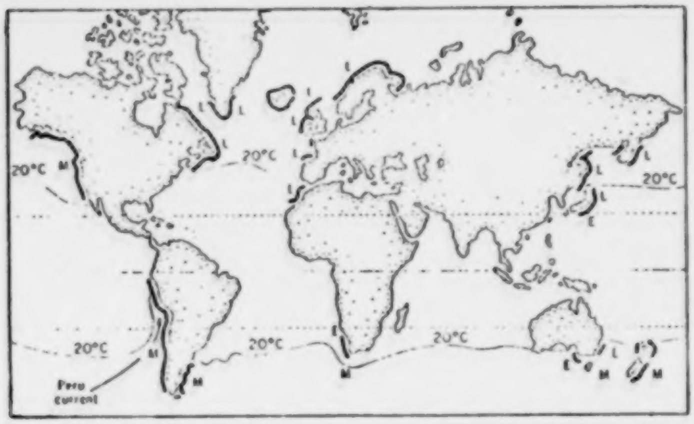

20°C
M
L
E
Peru current

Figure 65. Occurrence of kelps in quantities sufficient for commercial harvesting.

Note: L = Laminaria, M = Macrocystis, E = Ecklonia. The 20 C isotherms are for summer in the northern and southern hemispheres, respectively. The distribution of rockweeds (Fucales) is approximately the same as that of the kelps(227).

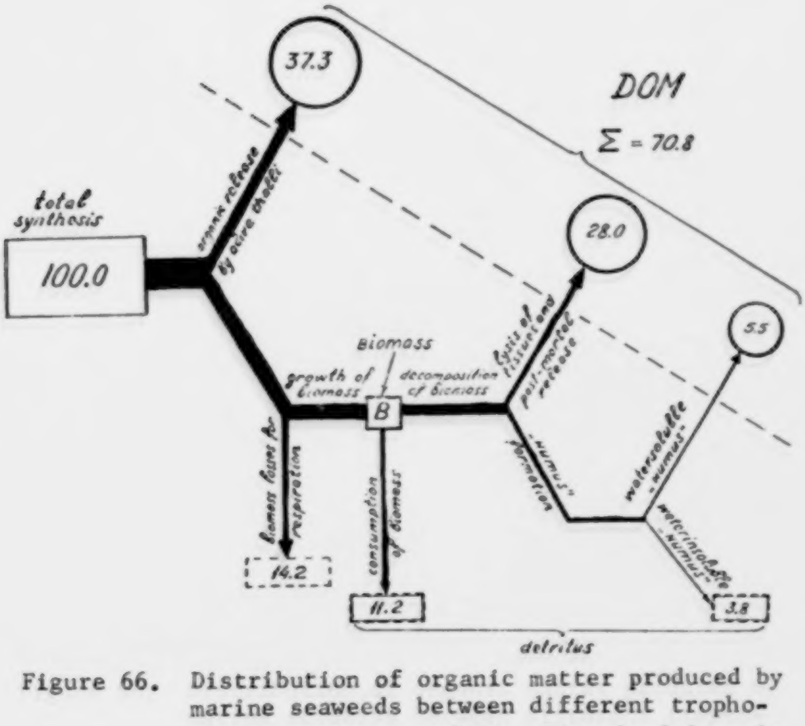

37.3
DOM
Σ = 70.8
total synthesis
100.0
organic release by active thalli
28.0
5.5
Biomass
growth of biomass
decomposition of biomass
lysis of tissues and post-mortal release
B
biomass losses for respiration
consumption of biomass
"humus" formation
watersoluble "humus"
waterinsoluble "humus"
14.2
11.2
3.8
detritus

Figure 66. Distribution of organic matter produced by marine seaweeds between different trophodynamical flows. (DOM = Dissolved Organic Matter).(228)

- The introduction of kelp into new areas of ocean may provide habitat for parasites and other undesirable pests, but may also be suitable for desirable populations.
- The present areal productivity in marine systems is insufficient to induce light-limitation in primary productivity except over restricted areas (Figure 66). The mats of blades are very dense and prevent assimilative ratios much in excess of that observed for a single layer because of shading(227). Studies on the influence of shading effects on species diversity were not located and may be negligible under most natural marine conditions. However, the areal scope of the harvesting program appears to justify some concern over this point.
- Open ocean farms have been proposed, and may circumvent many of the objections raised in the previous discussion, directed mostly at coastal waters application. However the technology of open ocean farming is embryotic in development, and raises a host of new technological problems. Environmental quantification of these should probably await favorable technological economic developments.

Environmental Consequence of Harvesting Transport--
Water emissions for harvesting/transport of feedstock are believed to be minimal on a routine basis, based on a comparison with transportation of oil by tankers or barges.(231) The possibility of an accident does exist; however, the probability of large spills of engine oil is low. Deck wash-down and other maintenance would contribute minor amounts of pollutants. Air emissions depend on the size and operations sequence chosen. The emission factors for various chemical species are shown in Table 96. These emissions are associated with internal combustion engines used to drive harvesters and transporters. Compared to the emissions from commercial fishing, shipping, and oil platforms, the incremental environmental costs due to emissions from harvesters engaged in kelp production for biomass are probably small.

Summary--
Ocean farming of kelp is an attractive concept for producing low-Btu gas in that minimal impact on present resource use is expected. Questions remain as to the availability of sufficient nutrients and sunlight to provide the degree of growth necessary to make this biomass source economically viable. Other issues pertaining to inter-species competition and alterations in marine materials cycling have also been raised. Emissions from harvesting and transport of the kelp appear minimal. Open ocean farming, as opposed to near-shore production, may eliminate or at least ameliorate these problems. In either case, the technology appears promising enough to warrant further study.

TABLE 96. AIRBORNE POLLUTANT EMISSION FACTORS - TRANSPORT/HARVESTING(231)

Parameter	Emission Factor kg/Vessel-km	Emission Factor (lb/Vessel-mi)
NO_x	0.40	1.4
SO_2	0.42(a)	1.5(a)
CO	0.34	1.2
Particulates	0.56	2.0
Hydrocarbons	0.25	0.9

(a) Assuming 0.5 percent sulfur content.

Marsh Harvesting

Physical/Chemical Impacts--

Marsh habitats are among the most productive and complex ecosystems known.(232) It is only within the past decade or so that the nutrient and trophodynamic aspects of marshes have been elucidated. The physical/chemical features of marshes which have been identified as possibly being altered as a result of harvesting are the following:

- Wetland vegetation buffers the coast regions against the erosive effects of wave, tidal, and wind action.
- The dense growth of plants commonly found in marshes acts as a sedimentation barrier preventing excessive siltation at the mouth of streams by creation of a distributary network and provides mineral soil for the marsh.
- The rate of water movement partially determines the exchange of dissolved nutrients among the compartments of the system.
- The soil temperature, pH, and radiation flux, are affected by the degree of cover.
- The organic matter contained in the harvested plant material may play a primary role in nutrient cycling.

The growth of marsh plants produces a network of root material and rhizomes which act to prevent erosion in much the same manner as a cover crop acts to prevent transport of soil particles from agricultural crop land. Different plant types may offer differences in their ability to prevent erosion. For example, a morphological study of growth by two marsh dominants showed that Glyceria maxima produced short-lived, shallow rhizomes while the Phragmites communis produced a persistent, deep seated rhizomes(233). In either case, the harvesting process would leave less material above ground to resist erosion, but the root stock would still provide a degree of protection. Some marsh soils are extremely fluid and depend on the fibrous root material to prevent losses of soil material. In these situations, harvesting may allow unfavorably high flows and result in land loss. Willingham et al(234) suggested that disturbance of marsh vegetation in relation to gas pipelining activities would create severe adverse impacts on the system.

The second, related point is that the development of a marsh at a mouth of a stream often causes the flow to be diverted from the main channel. Although most marshland is low-gradient, additional sedimentation is created by the flow reduction in the distributary network. Mineral soil loading to marsh soils is determined by the suspended load of the feeder stream and/or the tides. Cutting of vegetation may have the effect of increasing the flow rate and reducing the amount of sediment deposited in the marsh proper.

In addition to controlling sedimentation, the flow rate influences the exchange of dissolved substances between the marsh community and the water.

When photosynthesis is proceeding at a maximum rate, plants which depend on diffusion processes to supply a significant portion of nutrient needs can become nutrient limited. The suggestion has been made that upper bound values of productivity in intertidal marshes are observed which approximate those estimated from consideration of CO_2 availability(235). Thus, the advantages of a faster flowing system becomes obvious. For streamfed marshes the differences may not be significant but the case is not clear for tidal marshes. No specific studies were located which quantified the relationship between flow and nutrient supply in greater detail. However, Odum(232) stressed the importance of tidal action in maintaining a "subsidized" fluctuating water level ecosystem. In general, the higher the tidal amplitude the greater the production potential, provided that the ensuing currents are not too abrasive. The back and forth movement of water does the work of removing wastes and transporting food and nutrients so that organisms can maintain a sessile existence, which does not require expenditure of much metabolic energy.

The investigation of Pomeroy(235) also demonstrated that the daytime temperature of the sediments was influenced by insolation, shading by Spartina alterniflora, the greenhouse effect, and evaporation of water from the sediments. In winter the sediment temperature beneath dense strands of Spartina was lower than in base areas. Surprisingly, in summer the sediment temperature beneath dense growth was higher than that found for bare areas. This was suggested to be the result of a combination of greenhouse effects and reduced evaporation (see Figure 67).

It was also found that vegetal density influences the swings in pH which normally accompany diurnal changes in photosynthesis (Figure 68). However, the competing effects of increased pH due to high temperature (lower CO_2 solubility) and decreased pH (relative to an unshaded area) due to reduced photosynthesis were not resolved. Hydrogen ion activity changes in the bare areas were so marked that during the day the carbonate-bicarbonate equilibrium was shifted well to the right:

$$HCO_3^- \rightleftharpoons H^+ + CO_3^{2-}$$

At pH 10, the concentration of carbonate ion, which is largely unavailable as a carbon source for primary production, exceeds the concentration of bicarbonate by a factor of 2.5. The expected effects of harvesting would be to exacerbate this condition.

The amount of radiation reaching the algal flora of the marsh sediments varied not only with the season and cloud cover but also with the density of Spartina, the depth of water during the high tides, and the turbidity of the water (related to flow regime)(235).

The harvesting of plant material from marsh systems would have much the same impact as for harvesting of terrestrial agricultural residue, namely the alteration of soil structure and ion availability for plants. It has been suggested that the breakdown of organic material through decay processes serves in a positive chemical way by contributing nutrients directly and by adsorbing ions from the soil solution to be rendered available

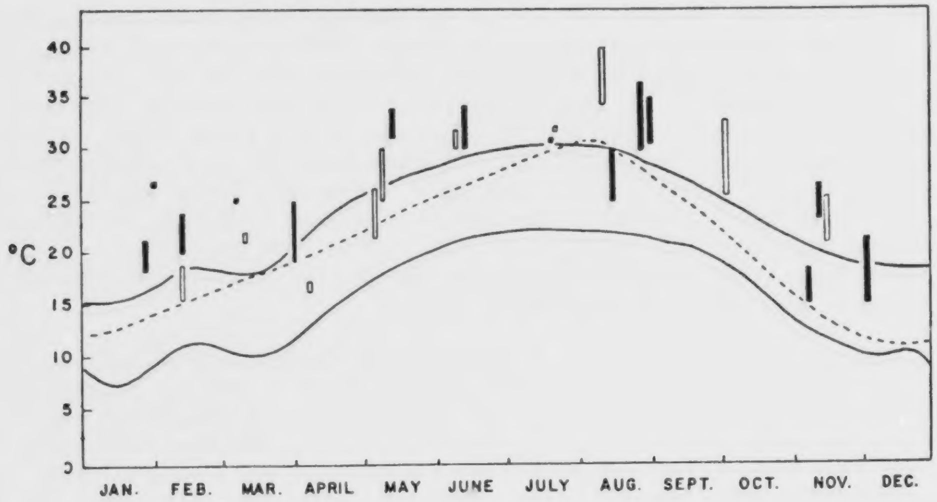


Figure 67. Seasonal variations in temperature in salt marshes near Sapelo Island, Georgia.(235)

Note: Solid vertical bars: Observed daytime temperature range of surface sediments under tall spartina. Broken line: Water temperature at mouth of Duplin River. Solid lines: Maximum and minimum air temperature at Sapelo Island (monthly means for 1956-57).

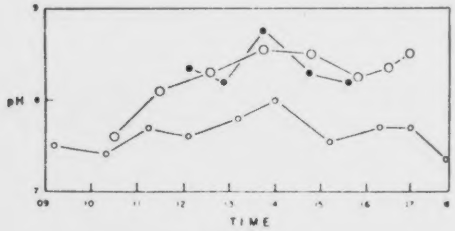


Figure 68. Diurnal variations in pH of the surface of the sediments of the salt marsh, south end of Sapelo Island.(235)

Note: Small open circles: Station in sparse, 0.3 meter spartina well back in marsh. Large open circles: Station in dense, 1-meter spartina on front of natural levee. Black dots: Station on bare strand. All were observed from first exposure by ebbing tide to covering by flood tide.

through ion exchange mechanisms(236). If this is true, then the leaching of nutrient elements becomes more pronounced. Measurements of soil parameters indicate that a host of variables influence the mineral and nutrient status of marsh soils(237). Among the most important are the degree of saturation, and humus content and to a lesser extent plant type. A highly consistent observation was that the more saturated the soil, the lower the organic content. Similarly, nitrogen on a dry-weight basis was positively correlated with humus content. The cation exchange capacity was also dependent on humus content, being very high in peaty soils. Thus if harvesting causes still lower humus levels, the productivity would further decline, especially in the wetter environments.

A very critical environmental problem not mentioned previously is the structural fragility of tidal marshes--only vehicles such as swamp buggies equipped with high flotation tires can be used. It is not clear how harvesting might be accomplished without destroying the vegetative mat at the same time or over the course of several years. This factor alone, if it cannot be resolved, may be enough to rule this out as a biomass source.

This compaction would essentially destroy the habitat, substantially reducing its value as either a natural or exploited resource. Consequently, successful development of harvesting equipment would appear essential before serious consideration of other environmental factors or, certainly, serious project development be undertaken.

Two factors mitigate the possible adverse impacts mentioned. The first is that seasonal influences already are imposed on the system. An annual die-back occurs in most growing areas during the fall and winter so that a single harvesting effort at this time could maximize the use of wetlands productivity for biomass fuel while minimizing the detrimental aspects. Storage of harvested material could become a substantial incurred cost under this alternative.

The second factor is that it may be possible to return the digested residue to the land. The ramifications of such an action should be considered in greater detail.

Expected Ecological Consequences--

As mentioned previously, marsh/wetland habitats have been identified as being ecologically complex. Indeed, the major impetus to their preservation has been their value in providing unique environmental niches. These areas have been documented numerous times as being critically important resources for the protection and maintenance of large numbers of different animal populations, including offshore fisheries.

No studies on the ecological aspects of marsh harvesting were located. However, a study of coastal ecosystems, probably spanning the range of those likely to be encountered in a harvesting effort, identified several hundred species in more than 20 phyla. Because of the narrow range of growth requirements of marsh plants, a high degree of sensitivity to modifications of their habitat was noted(234). Other ecological changes that might be induced through a harvesting program include removal of forage and cover for small animals, alterations in species composition due to changes in the physical/chemical environs, and differences in food webs. More detailed evaluations of actual sites are needed; each area is likely to be impacted differently and generalizations beyond those briefly stated above would be unwarranted.

Summary--

The marsh community represents an extremely complex web of physical, chemical, and ecological interactions which is just beginning to be understood. What is known seems to justify the statement that marshes provide important benefits for receiving bodies of water and protect valuable ecological niches. Moreover, marshes are fragile and extreme caution is warranted in utilizing these biomass sources.

Municipal Solid Waste (MSW)

Introduction--

The present technology for dealing with municipal solid waste emphasizes disposal mostly by landfilling rather than recycling. In some applications, volume reduction is achieved through shredding and incineration. In addition, ferrous metals recovery is practiced where economically feasible. Several alternatives aimed at the conversion of this waste to usable energy have been suggested or are being examined on varying scales. These may be classified as preparation of solid waste as a supplemental or primary fuel for direct combustion; pyrolyzation to produce gas, oil, and char; and anaerobic fermentation to yield methane and solid by-products. The supplemental fuel and pyrolysis options are best discussed in the context of environmental impacts of conversion processes (see - Impacts Associated with Biomass Conversion to Fuel/Energy). The third alternative is similar in some ways to another minor disposal method for solid waste which has enjoyed a recent upsurge of interest, that is, the practice of composting. This is important from an environmental viewpoint, because it represents an alternative use for a biomass source, which may have positive environmental significance.

Composting is a practice which stabilizes a waste material by the action of thermophilic aerobic bacteria; the principal gaseous products are CO_2 and water vapor. While the degradation processes and decomposition gases are somewhat different from anaerobic fermentation, the solid residue is expected to exhibit similarities in most physical and some of the chemical characteristics. The results and implications of field experiments carried out in this area as related to land application of anaerobic fermentation residues will be compared with those now experienced with landfilling, the most widely used and least costly method of disposal in the U.S. No attempt will be made to comprehensively treat the environmental implications of disposal/recycling of municipal solid waste. Several excellent reviews of the state-of-the-art of the relevant technology and characterization methods are available in the open literature.

Characteristics of Raw and Composted Municipal Solid Waste--

Domestic refuse is composed or organic food wastes; paper and paper products; wood; plastics, leather, and rubber materials; rags and textile products; glass; metallics; inert stone, clay, and earthen products; and yard wastes(238).

The type of refuse and percentage by volume and weight are listed in Table 97. It can be seen that four of the eight categories would contribute substantially to the BOD/COD and nitrogen content of leachate from a landfilling operation. Furthermore, the wide range of degradation rates would prevent rapid stabilization. Depending on pH, hydraulic conditions and oxidation/reduction potential, metal species may also be mobilized to varying degrees. Table 98 lends credence to this interpretation. By comparison, a solid residue produced from municipal solid waste by composting contained lower values of N and P and was high in organic content. The BOD of leachate from treated plots was not determined in this study(240). It is suggested that the leachate from anaerobically digested solid waste would more closely resemble the "old" than the "new" leachate characteristics (Table 98).

Incorporation of composted material over a two-year period effected a statistically significant change in several physical and chemical soil parameters (Table 99). Overall, the land application of carefully prepared, composted solid waste seems to be beneficial, although the zinc increases may be indicative of other heavy metal behavior.

Summary--

It appears the utilization of urban waste as fuel is a promising alternative environmentally in that:

- The feedstock is already centralized and a reasonably efficient collection system exists,
- A reduction in volume by a factor of two to ten is possible and desirable,
- Ferrous and non-ferrous metals and glass and other ceramics may be recoverable,
- The solid residue from some processes may be useful as a soil amendment to increase tilth and water holding capacity, although supplements of fertilizers may still be required for optimal crop growth,
- The BOD content of the liquid waste stream from biological processes can be reduced by conventional treatment.

The drawbacks are that the question of heavy metal concentration increases (in regard to digester operation and soil incorporation) has not been fully determined and that the economics of transportation of the solid by-product have not been worked out in detail. The former may not be significant if the pH is maintained at or slightly above neutral.

TABLE 97. CHARACTERISTICS AND DISTRIBUTION OF TYPICAL MUNICIPAL SOLID WASTE(238)

Category of Refuse	*Percent by Weight*	*Percent by Volume*
Paper and Paper Products	32.98	62.61
Wood and Wood Products	0.38	0.15
Plastic, Leather, and Rubber Products	6.84	9.06
Rags and Textile Products	6.36	5.10
Glass	16.06	5.31
Metallics	10.74	9.12
Stones, Sand, and other inerts	0.26	0.07
Garbage (organics)	26.38	8.58

TABLE 98. CHARACTERISTICS OF LEACHATE AND WASTEWATER(239)

Constituent†	Leachate Fresh	Leachate Old	Waste-water	Ratio
TSS	327	266	200	1.6
TDS	12,620	1,144	—	—
Conductivity	9,200	1,400	700	13
pH	5.2	7.3	8.0	—
COD	22,650	81.1	500	45
BOD	14,950	—	200	75
TOC	6,500	70.0	200	32
Total P	7.35	4.96	10	0.7
Total N	989	7.51	40	25
Chloride	742	197.4	50	15
Calcium	2,136	254	50	43
Magnesium	277	81	30	9
Iron	500	1.5	0.1	5,000
Manganese	49	—	0.1	490
Zinc	45	0.16	—	—
Copper	0.5	0.1	—	—

*Source: *Characteristics of Percolate of Solid and Hazardous Waste Deposits.*[2]

†All constituents reported as mg/l except Conductivity, which is reported as micromhos/cm. and pH, which is the logarithm of the reciprocal or the hydrogen activity in moles per liter.

TABLE 99. EFFECT OF COMPOST AND NITROGEN ADDITION ON PHYSICAL AND CHEMICAL CHARACTERISTICS OF SOIL AT MUSCLE SHOALS(240)

2-year total compost application	Annual N rate	Moisture holding capacity at 1/3 bar	Soil moisture	Bulk density*	Unconfined compression strength	Organic matter	pH	Extractable nutrients			
								K	Ca	Mg	Zn
metric tons/ha	kg/ha	%			kg/cm^2	%		kg/ha			
0	0	11.1	12.4	1.37 a	2.9 a	1.58	5.4	193	1,653	181	7
0	180	--	11.0	1.37 a	2.3 b	1.47	5.1	155	1,472	156	6
46	0	--	12.5	1.32 ab	2.9 a	1.81	6.2	197	2,341	199	29
46	180	--	11.6	1.30 bc	2.6 ab	1.99	6.0	146	2,285	193	35
82	0	--	12.9	1.27 cd	2.6 ab	1.96	6.2	230	2,610	206	38
164	0	13.0	13.3	1.22 e	2.4 b	2.66	6.6	378	3,349	224	91
327	0	15.3	14.8	1.12 f	1.5 d	4.22	6.8	332	3,920	234	490
164	180	--	13.5	1.25 de	1.9 c	2.58	6.4	215	3,181	189	86

*Values having the same letter in each column are not significantly different at the 95% level.

IMPACTS ASSOCIATED WITH BIOMASS CONVERSION TO FUEL/ENERGY

The transformation of biomass feedstock to fuel/energy can be accomplished in a number of ways, some direct and some indirect. The concomitant production of solid, liquid, and gaseous waste streams is of concern, although a given process may not produce waste streams in all forms. It is the purpose of this section to review the various generic classes of conversion methodologies and to describe the residuals in a qualitative and semi-quantitative manner. In some cases, information of interest is lacking or incomplete. Such gaps will be bridged by drawing inferences from available data on other technologies where feasible, or identified as areas where research needs are indicated.

Direct Conversion

Energy conversion in the form of process heat or power production can be accomplished by the biomass sources addressed in the preceding section of this chapter. However, the difficulties in maintaining a stable combustion zone for high moisture sources such as animal waste or kelp and/or the cost of drying these to a suitable level will likely limit the application of direct conversion to relatively "dry" sources such as municipal solid waste (MSW) and air-dried wood/agricultural crop residue.

Emission factors for direct conversion are available for the burning of an admixture of refuse and coal, the burning of refuse alone, and for combustion of wood residue and bagasse. Table 100 lists the gaseous and particulate emission factors for these four feedstocks and includes traditional coal combustion for comparison. It can be seen that biomass sources appear favorable in terms of SO_x and NO_x emissions because of the very low levels of these pollutants in the fuels. Particulate emission levels are higher for the most part, but it is suspected that these would be reduced if effort were expended to produce energy from these sources on a greater scale. Carbon monoxide and hydrocarbon emission factors for wood residues are probably higher because of the high lignin to cellulose ratio, the higher moisture content when burned and the lower resultant flame temperature. In addition, the particulates, especially from MSW, will contain inorganic materials, including detectable amounts of free mercury and beryllium, lead, zinc, cadmium, nickel and vanadium (see Tables 101 and 102).

These heavy metals and others, such as selenium, are potential health hazards, whose overall effect at low exposure levels is poorly known at present. Lead particulate inhalation may cause chronic intoxications; soluble lead components are cumulative poisons. Particulate beryllium produces pulmonary fibrosis. Cadmium oxide dust or fumes may cause pulmonary edema or hemorrhage. Zinc inhalation may lead to "metal fume fever" and damage to the respiratory tract.

TABLE 100. PARTICULATE AND GASEOUS EMISSION FACTORS FOR DIRECT COMBUSTION OF BIOMASS COMPARED WITH COAL COMBUSTION

Source	Kg/10^6 Btu				
Parameter	MSW$^{(a)}$	MSW + Coal$^{(b)}$	Wood Residue$^{(c)}$	Bagasse$^{(d)}$	Coal$^{(e)}$
Particulates	0.04-0.8	>0.04	0.6	1.1	0.04
SO_x	0.1	0.4	0.06	0	0.5
NO_x	0.2	0.3	0.4	0.1	0.3
CO	0.04	0.04	1.2	0.1	.04
HC	—	—	1.4	0.1	.02

(a) Hughes, et al.,(241); Surprenant,(242). 10 kg particulates/ton refuse; 6000 Btu/lb heating value; second value refers to untreated refuse and first value is 95% collection efficiency.
(b) 11,100 Btu/lb at 12 percent refuse content (wt/wt basis).
(c) Surprenant,(242). Assumes 6000 Btu/lb heating value.
(d) Surprenant,(242). Assumes 4600 Btu/lb heating value.
(e) Surprenant,(242). Assumes bituminous coal, stoker feed, 3% sulfur content, 15% ash, 12,000 Btu/lb heating value.

TABLE 101. CONCENTRATION OF SOME TRACE MATERIALS IN INCINERATOR FLY ASH(241)

Species	Study 1 (amount)	Study 2 (percent)
Be	Small or trace	0.001-0.01
Hg	Small or trace	
Pb	Small or trace	0.01-0.1
Zn	Small or trace	1-10

TABLE 102. EMISSION FACTORS FOR MUNICIPAL INCINERATORS (242)

Element	Sample Conditions	Emission Factor 10^{-3} kg/MT refuse burned
Be	Uncontrolled	0.015
	ESP[a]	0.015
Cd	Uncontrolled	1.55
	Wet scrubbed	0.4
Mn	Uncontrolled	15.0
	ESP	3.5
Hg	Uncontrolled	0.5
Ni	Wet Scrubbed	1.5
V	Uncontrolled	0.5
Pb	Uncontrolled	16.0

(a) Electrostatic precipitator.

Fluidized-bed incineration will probably produce no more airborne particulates than will normal incineration if both facilities are properly managed(241). In fact, the Combustion Power Company process in which combustion gases are fed to a turbine to generate electricity requires extreme cleanliness. Particles and metal vapors can cause erosion and other problems with turbine blades; thus, the process includes three stages of cyclone separation for particle removal.

Fluidized-bed processes can usually be adjusted so as to absorb sulfur dioxide into the bed. The low combustion temperatures in the bed are expected to reduce nitrogen oxide formation. This better thermal contact should also reduce the quantities of unburned organic material, including chlorinated and polynuclear hydrocarbons.

Combustion (incineration) processes in which refuse makes up a small fraction of the total material fired will operate under the same general conditions and produce the same general environmental effects as coal-fired boilers.

Other volatile materials may escape combustion at low excess air values. These may cause problems with eye irritation and odor but are not fundamentally hazardous. Formic, acetic, palmitic, stearic, and oleic acids; methyl and ethyl acetate and ethyl stearate; formaldehyde and acetaldehyde, hydrocarbons, and phenols have been found in incinerator stack gases.

Hydrogen chloride can be an undesirable product when chlorinated hydrocarbons (such as those contained in PVC plastic films) are burned. Proper incineration practice, including after-burning with additional fuel, should reduce all of these to unnoticeable or negligible levels, although this does not avoid the severe corrosion problems. Emissions of metals and organics from feedstocks other than MSW are not well characterized.

Incineration may also produce liquid wastes, although the necessity for water quenching may not exist for all plants. It has been estimated that 5 to 50 liters (1 to 10 gallons) of quench water will be discharged per ton of refuse treated(241). Water required for other operations may also be discharged. Cooling system and boiler blowdown/system cleaning water is discharged intermittently. Ash handling may create a wastewater stream other than that generated with the quench water.

Depending on the contact time and ambient conditions, the quench/ash handling water may become highly caustic due to ash composition and contain suspended and dissolved solids. This process stream will require neutralization and sedimentation. Most heavy metals entrained in the bottom ash should not be leached at alkaline pH values if contact times are short.

BOD and COD may be high. Although most putrescible material will have been destroyed, not all of the organic material, especially wood fiber is burned. Burning under conditions of excess air should prevent formation of reduced metal salts. Wash water and other system water needs will contribute organics such as oil and grease, detergents, algae and corrosion inhibitors, and so forth. The incorporation of pre-treatment facilities providing primary or secondary treatment internal to the conversion plant may need to be considered.

Solid residuals amount to between 180 and 225 kg per ton of MSW, most of which will likely find its way into a landfill. The composition of this material is principally silicon, aluminum, calcium, and iron oxides but may vary in the proportion of each depending on the characteristics of a particular waste. Leachates from landfills may percolate to ground waters, streams, and so forth. These leachates will have high hardness, but the composition and quantity are too dependent upon local conditions for any judgement of their ultimate environmental effect to be made without extensive field work and analysis. The environmental impact analysis for an individual location must define the potential effects. Incineration should mitigate common landfill problems such as high BOD and nitrates in leachate, vector production, and disturbance of large tracts of land.

Solid residues from biomass sources other than MSW may also produce highly mineralized leachates. The ash composition resulting from combustion of wood/bark, animal waste, and agricultural residue is shown in Table 103. The analyses indicate that other ash compositions are similar to those generated by MSW so the above statements concerning the characteristics and contamination potential from the leachate should be equally valid. It has been suggested that the ash be returned to the soil as a fertilizer because it contains significant mineral and nutrient resources; however, the question of heavy metal levels and behavior remains unanswered.

Table 104 lists the levels of several trace elements in MSW; others are undoubtedly present.

Several of the feedstocks may require drying of the as-received substance on an occasional or regular basis. (As-received refuse may have from 20 to 90 percent water; 30-35 percent is very common.) This drying and the combustion of the material will release moisture to the environs of the plant. Drying can produce noxious odors in the drying gas stream. Most of this can be removed by passing the exit gas through a high-temperature flame, 700 to 820 C (1300-1500 F). This requirement for an extra combustion step and necessity for extra fuel could reduce the economic attractiveness of the process that requires it. Use of exit air for primary or secondary incinerator air source may partially relieve this constraint.

Handling, size reduction, and classification activities create dusts, especially if the solid waste has been dried. The operator and designer must take potential dusting into account so as to minimize its effects. Vents or hoods over the equipment can lead the dusty air to a separate filter system or to the main stack. Total particulate discharge will not be measurably affected, and this impact can be controlled in the context of total particulate discharge.

TABLE 103. ASH ANALYSIS OF BIOMASS FEEDSTOCKS

	Percent by Weight						
Species	Southern Pine(a)	Pine Bark(a)	Oak Bark(a)	Spruce Bark(a)	Corn Stalks(b)	Cattle Manure(c)	MSW(d)
SiO_2	19.0	39.0	11.1	32.0	*	*[e]	50.0
Fe_2O_3	1.0	3.0	3.3	6.4	0.3	5.5	7.9
TiO_2	*	0.2	0.1	0.8	*	*	0.9
Al_2O_3	21.0	14.0	0.1	11.0	*	*	11.4
Mn_3O_4	*	Tr.	Tr.	1.5	0.1	*	*
CaO	27.0	25.5	64.5	25.3	2.1	6.8	12.2
MgO	5.0	6.5	1.2	4.1	1.8	3.2	1.3
Na_2O	3.0	1.3	8.9	8.0	*	13.0	8.8
K_2O	9.0	5.0	0.2	2.4	8.2	11.6	1.6
SO_3	6.0	0.3	2.0	2.1	2.0	4.0	1.5
Cl	*	Tr.	Tr.	Tr.	1.4	*	*
P_2O_5	4.0	*	*	*	3.2	8.8	1.4

(a) Abstracted from Table 5.
(b) Gerloff, G. C. unpublished data.
(c) Referred to 3.1 percent ash content and Table 11.
(d) Surprenant, (242).
(e) Asterisk indicates not reported.

TABLE 104. TRACE ELEMENTS IN REFUSE ASH(242)

Species	Mean Weight Percent
SnO_2	0.05
CuO	0.32
ZnO	0.41
PbO	0.19

In any discussion of environmental effects, it should be noted that most solid waste-disposal processes will require collection, with the attendant noise and environmental effects of large truck transportation. At the collection station, the noise of transfer operations and the odors coming from untreated material in storage will create localized problems. Size reduction, which is essential for some processes and desirable for any materials recovery operation, is very noisy. Relatively small shredders capable of handling 5 metric tons per hour will produce noise levels of 80 to 85 decibels at 50 feet from the machine. This is equivalent to the noise arising from diesel trucks, compactors, and other equipment to be encountered at disposal sites. The noise impact will be restricted to a relatively small area in the immediate vicinity of the plant. Health hazards, such as pathogens, carcinogens, and metals to which the plant attendants might be exposed, need to be evaluated in greater detail.

Pyrolysis

Emissions from the conversion of biomass to energy via pyrolysis may occur at two stages: the production of the energy product (gas or oil) and the combustion of the product at a final destination. The latter evaluation is nearly impossible on a quantitative basis since the distribution scheme and disposition for the product are unknowns. Qualitatively, the emissions should not be grossly different than those already existing.

Preliminary studies on the air emissions resulting from combustion of pyrolytic oil produced by the Garrett process tends to affirm this line of reasoning(243). In converting solid waste to a liquid fuel, one of the primary objectives is to produce a substance that burns cleaner than the original solid waste. Limited test data have been collected on emissions of sulfur dioxide and oxides of nitrogen produced when the pyrolytic oil is burned. Concentrations of sulfur dioxide in the flue gas were directly proportional to the sulfur content of the fuel. They ranged from 120-155 parts per million (ppm) when the fuel was blended with No. 6 oil (having a sulfur content of 0.4 percent) up to 290 ppm when 100 percent pyrolytic oil was burned. This compares quite favorably to the 380 ppm produced when No. 6 fuel oil having a 1 percent sulfur content was burned. Nitrogen oxide production was somewhat higher for the pyrolytic oil than No. 6 oil. Blends of No. 6 fuel oil and the pyrolytic oil produced an average of 420 ppm of oxides of nitrogen. Additional experimentation with various firing methods is needed to determine the impact this fuel will have on emissions of oxides of nitrogen. In order to assess fully the environmental impact of this fuel, the San Diego Gas and Electric Company has proposed a 21-month test program incorporating both laboratory and boiler tests. Flue gas analysis will include particulates, oxides of nitrogen, oxides of sulfur, hydrochloric acid, carbon monoxide, and visible emissions(243).

The direct emissions from pyrolysis production processes should be small. The product gases from each will be contained and can be scrubbed to remove acid gases (H_2S, CO_2) and particulates. The entire gas output of the Torrax and Union Carbide processes will be so treated. The Bailie process produces separate streams of product and combustion gas. The latter will be quite small in volume when compared to that from direct incineration processes. Only 10 to 15 percent of the combustibles will be directly burned. The burning, in a fluidized-bed, should require little excess air, produce only small quantities of nitrogen oxides, and have low unburned hydrocarbon loads.

Ash loads from several of these processes will approximate those from direct incineration. The fluidized-bed of the Bailie process will produce about 50 percent more ash than the other processes. Thus, the landfill requirement is larger and leachate loads may be slightly higher for it than from the other processes.

A flow schematic described previously (Figure 23) on the Garrett process makes quantitative and qualitative estimation of residual streams possible. However, this analysis should be considered as representing only a single feedstock and set of operating conditions. The materials balance for a 1000 ton/day plant is shown in Table 105. Residuals generated in water or gas treatment are not included nor is the additional water input to the spray separator column.

Analyses of the gaseous fraction of pyrolysis products indicate high concentrations of hydrocarbons (~ 20 volume percent) and carbon monoxide (42 volume percent). However, the secondary combustion of the pyrolysis gas for process heat will consume some of the hydrocarbons and other combustibles. The gas burned in this step has a low heating value so that flame temperatures are lower than in incineration. Estimated air emissions for pyrolysis and incineration are compared to those from coal and oil in Table 106.

The results in Columns 1 and 2 in Table 106 for municipal waste treatment are not, of course, strictly comparable since different wastes were used and could have varied quite widely in composition. The higher sulfur dioxide level in the pyrolysis stack gas, as compared to the incineration stack gas, is the result of two possible situations: (a) a higher sulfur content in the waste or (b) the smaller stack gas volume. In any event, it is obvious that municipal refuse contains much less sulfur than that in

TABLE 105. MATERIALS BALANCE - GARRETT PROCESS(a) (1000 tons/day input)

Stream Description	Tons/day
Screened glass from light fraction	21
Char from pyrolysis products	80
Pyrolysis gases (before combustor)	157
Product pyrolysis oil	240
Ferrous metals	70
Non-ferrous materials	55
Screened glass ceramics to rod mill (82 tons recoverable product)	100
Water	277 (+ spray inputs)
Total	1000

(a) Abstracted from Figure 23, p. 124.

TABLE 106. STACK GAS PPM BY VOLUME CORRECTED TO 12% CO_2 (245)

	Municipal Waste		Other Fuels		
	Pyrolysis	Incineration	Natural Gas	No. 6 Fuel Oil	Coal
Sulfur dioxide	130	100	0.3	500(a)	3,500(b)
Nitrogen oxides	55	80	170	450	360
Hydro-carbons	9	17	—	6	12
Chloride	20	440	—	—	—
Particulates, gr/scf	0.03	0.04	0.01	0.02	1

(a) Not given in reference; 0.5-3.5 percent sulfur by weight is typical (Finney and Garrett, 246).

(b) Not given in reference; 0.4-4.0 percent sulfur by weight is common (Surprenant, 242).

No. 6 fuel oil or coal. The low nitrogen oxides in the pyrolysis stack gas reflect the generally lower temperatures compared to those of combustion processes. The unburned hydrocarbons are not significantly different, but the total emission from a pyrolysis system would be lower than from the others because the volume of flue gas produced per ton of fuel is lower. The lower chloride content in the pyrolysis gas probably reflects a major difference in the waste composition, e.g., content of PVC plastic. The particulate concentration from pyrolysis and incineration do not differ significantly, but the total mass emission from a pyrolysis system would be lower, again because of a smaller flue gas volume. Whether particulate, hydrocarbon, and nitrogen oxide emission levels in actual operation are lower for pyrolysis plants than for incineration plants is probably more dependent upon individual differences in design and methods of operation than upon process fundamentals(244).

Pyrolysis processes such as Landgard, that produce steam as a principal product, will have air emissions similar to those of the combustion systems. Exit gas flows lie between those found in normal incineration and those in combined burning with coal.

As noted earlier, the lower quantity of air required for pyrolysis/gasification as compared to incineration should result in less entrainment of particulate materials in the off-gases from the reactor. Since the off-gas will be further reacted in a combustion process, any combustible particulates, e.g., char or tar mists, will be re-exposed to oxidation conditions during the combustion process. Other particulates like sand or grit can generally be removed from the off-gas by a variety of means, and it is likely that this will be done prior to the combustion of the gas.

One form of particulates is, however, of concern. It is known that certain metals can be produced as a fine particle fume or smoke in a thermal process. Among these are lead and zinc which are known to be toxic. Another potential problem that may be encountered in pyrolysis/gasification is related to the fact that certain metals can form gaseous and toxic carbonyls by reaction with carbon monoxide, one of the gaseous products of the process. There is no indication that such measurements or even total metal emissions determinations have been carried out(245).

During the pyrolysis step, water and organic compounds are formed and distilled from the biomass material. While the resulting mix is somewhat variable depending on the nature of the feed materials, the water fraction has been shown to contain a variety of aldehydes, ketones, alcohols, phenol, acids, etc.(247). It was stipulated that, although the BOD of such a waste stream is high, the quantity of water is low relative to typical municipal waste loads(246). Treatability is not expected to be a problem if a conventional secondary sewage treatment plant (STP) is incorporated into the design or is available nearby. System wash water and water used in separators are also likely to contain significant amounts of water soluble organics and should be treated. The BOD of these mixtures is estimated to be in the range of 500-3000 mg/l. Generally, the BOD values for municipal secondary influent are in the range of 150-250 mg/l(220). Thus, the imposition of the untreated waste load from a large pyrolysis plant on a municipal STP represents a high organic load, especially if discharged as a slug flow. The small volume should be a mitigating factor as dilution ratios will be high.

Most of the pyrolysis processes produce a solid char or ash which contains the major portion of the metal content of the original feedstock together with small amounts of nitrogen, sulfur, and chlorine. A portion of the char may be used for heat (as is the case for the Garrett process). The char material thus produced has been assigned little market values and, unless a technological breakthrough occurs, is likely to be landfilled. A small fraction of the inert solids produced by other pyrolysis schemes, such as the Battelle or Torrax processes, can be utilized as a construction aggregate; however, the main portion will probably be landfilled. Relative to disposal of these materials, all of the pyrolysis technologies represent a reduction in volume and, at least, partial stabilization of the solids. Some BOD/COD will remain; however, it should be well below that of raw feed and the metals. Since it is concentrated into a smaller volume, the metal content of the original material will be amplified. Whether the pyrolysis conditions enhance the mobility of metals has not been experimentally determined.

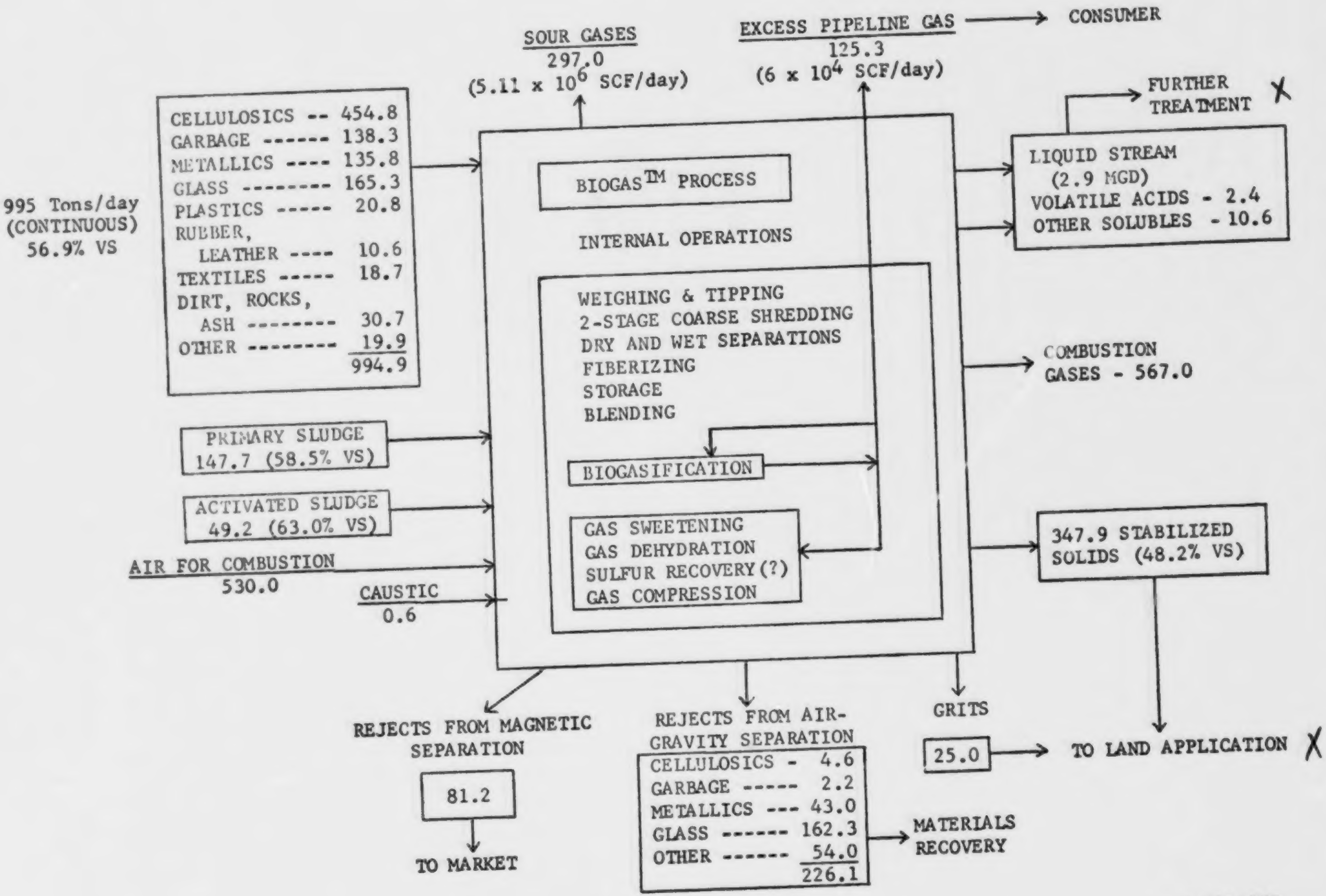
Anaerobic Digestion

The conversion of biomass to methane and carbon dioxide by the action of obligate anaerobic bacteria produces, in addition to the product gas, an aqueous slurry which is generally dewatered. Dewatering may be passive as in sedimentation/flotation or active as with vacuum or pressure filtration. The degree of dewatering will influence the problems associated with the disposal/recycling of the solid cake. Other operations involved are the following.

- Size reduction - shredding
- Removal of metals and chlorinated hydrocarbon plastics
- Addition of nutrient material (necessary if MSW is used as feedstock)
- Gas scrubbing - removal of CO_2 and H_2S.

Several processes have been conceptualized; however, the Dynatech system and the Biogas process have proceeded farthest towards commercialization. The material balance for a nominal plant size of 1450 metric tons/day (1600 ton/day) using the Biogas process as shown in Figure 69. The plant is expected to gasify 39 percent of the solids and liquefy an additional 1 percent. Thirty-one percent are disposed/recycled as sludge and the remaining 29 percent are recoverable secondary products. It has been estimated that the production of each cubic meter of methane (at standard conditions) from MSW removes 2.9 kg of COD/BOD relative to the original raw waste(249).

The atmospheric emissions are expected to be minimal with the possible exception of H_2S contained in the product gas and possibly the refuse-sludge blending system, if used. An acid-gas scrubber will probably be used to upgrade raw product gas to pipeline quality.


SOUR GASES
297.0
(5.11 x 10^6 SCF/day)
EXCESS PIPELINE GAS
125.3
(6 x 10^4 SCF/day)
CONSUMER
FURTHER TREATMENT
995 Tons/day
(CONTINUOUS)
56.9% VS
CELLULOSICS -- 454.8
GARBAGE ------ 138.3
METALLICS ---- 135.8
GLASS -------- 165.3
PLASTICS ----- 20.8
RUBBER, LEATHER ---- 10.6
TEXTILES ----- 18.7
DIRT, ROCKS, ASH -------- 30.7
OTHER -------- 19.9
994.9
BIOGAS™ PROCESS
INTERNAL OPERATIONS
WEIGHING & TIPPING
2-STAGE COARSE SHREDDING
DRY AND WET SEPARATIONS
FIBERIZING
STORAGE
BLENDING
BIOGASIFICATION
GAS SWEETENING
GAS DEHYDRATION
SULFUR RECOVERY (?)
GAS COMPRESSION
LIQUID STREAM
(2.9 MGD)
VOLATILE ACIDS - 2.4
OTHER SOLUBLES - 10.6
COMBUSTION GASES - 567.0
PRIMARY SLUDGE
147.7 (58.5% VS)
ACTIVATED SLUDGE
49.2 (63.0% VS)
AIR FOR COMBUSTION
530.0
CAUSTIC
0.6
347.9 STABILIZED SOLIDS (48.2% VS)
REJECTS FROM MAGNETIC SEPARATION
81.2
TO MARKET
REJECTS FROM AIR-GRAVITY SEPARATION
CELLULOSICS - 4.6
GARBAGE ----- 2.2
METALLICS --- 43.0
GLASS ------ 162.3
OTHER ------ 54.0
226.1
MATERIALS RECOVERY
GRITS
25.0
TO LAND APPLICATION
X
X
B-34-495

(ALL FIGURES ARE IN TONS/DAY UNLESS INDICATED OTHERWISE)

Figure 69. Mass balance summary for a 1600 ton/day biogas plant. (Reference: Ghosh and Klass, 248)

Ancillary operations may generate noise and dust, but these ought to be mainly local in impact and can be minimized.

The stripping column in this case will produce a gas stream rich in CO_2 and also containing essentially all the H_2S and related compounds (odorants) produced by the digestor. For smaller systems, it is likely this stream will be emitted (after burning) to the atmosphere. For very large systems, it may be possible to install a Claus plant for recovery of sulfur content as elemental sulfur or sulfuric acid. The most likely situation, however, is that the H_2S will be controlled by oxidation to SO_2 and reaction with lime. This scheme will produce a relatively small sludge stream for disposal.

More difficult to handle may be the air quality problems encountered during off-specification operations. These will probably be caused by poisoning of the bacteria either by metals or acid. The "sour" partially treated, reactor contents are vile-smelling, due to low-molecular weight, volatile acids such as butyric and propionic. Its disposal by landfill (the most likely alternative) would be perceived by people for several miles downwind from a large plant and/or a disposal site, and would undoubtedly draw unfavorable reactions.

Water quality may be a problem for several reasons. The BOD of the liquid stream is approximately 500 mg/l and suspended solids may be greater than 700 mg/l. Of itself this presents little difficulty since standard BOD removals in secondary treatment are on the order of 80 percent and SS removals approximately 90 percent. However, the maintenance of slightly acidic pH conditions and long detention times may be conducive to leaching of metals from the solids, if insufficient sulfide is present. The actual metals content of the digestor supernatant is unknown.

Studies on the metal content of the solid residue could not be located. In terms of total metal content, the values from a composting process will give order-of-magnitude indications of concentrations (see Table 107). Comparative studies of metal content in effluents from digestion processes currently under development need to be made.

Solid residues may be landfilled with the attendant BOD/COD, ammonia, solids, and metals control requirements. A second alternative is landspreading as a soil amendment if metals are immobilized.

The fact that anaerobic digestion is a microbiological process does partially mitigate concern about heavy metal toxicity. As shown in Table 108, prepared for mesophilic anaerobic digestion only, unsuccessful operation would likely occur if the metal content in solution exceed greatly the moderately inhibitory values. However, the toxicity of continuous land application over a long term with commensurate heavy metal build-up remains an unanswered question.

Table 109 compares the physical and chemical characteristics of the anaerobic digestor substrates. It can be seen that these are complementary in nature and that sewage sludge might be added for nutrients. The effluent characteristics are listed in Table 110 as a function of

TABLE 107. ELEMENTAL CONTENT OF 42 DAY-OLD COMPOST AT JOHNSON CITY (249)

Element	Percent dry weight (average)		Range (all samples)
	Containing sludge (3%-5%)	Without sludge	
Carbon	33.07	32.89	26.23 - 37.53
Nitrogen	0.94	0.91	0.85 - 1.07
Potassium	0.28	0.33	0.25 - 0.40
Sodium	0.42	0.41	0.36 - 0.51
Calcium	1.41	1.91	0.75 - 3.11
Phosphorus	0.28	0.22	0.20 - 0.34
Magnesium	1.56	1.92	0.83 - 2.52
Iron	1.07	1.10	0.55 - 1.68
Aluminum	1.19	1.15	0.32 - 2.67
Copper	< 0.05	< 0.03	
Manganese	< 0.05	< 0.05	
Nickel	< 0.01	< 0.01	
Zinc	< 0.005	< 0.005	
Boron	< 0.0005	< 0.0005	
Mercury	not detected	not detected	
Lead	not detected	not detected	

TABLE 108. STIMULATORY AND INHIBITORY CONCENTRATIONS OF METALS AND OPERATING PARAMETERS FOR MESOPHILIC ANAEROBIC DIGESTOR PROCESSES USED IN SEWAGE SLUDGE TREATMENT

Parameter	Stimulatory	Moderately Inhibitory	Strongly Inhibitory	Reference Source
Sodium, ppm	100-200	3500-5500	8000	250
Potassium	200-400	2500-4500	12,000	250
Calcium	100-200	2500-4500	8000	250
Magnesium	75-150	1000-1500	3000	250
Ammonia Nitrogen	50-200	1500-3000	3000	250
Sulfide		100-160	200	250
Temperature, C	30-35	25 and 40		251
pH	6.8-7.4	6.2 and 7.8		251
Volatile Acids	50-5000	20,000		251
Alkalinity	2000-3000	1000 and 5000		251
Chromium (VI)	< 50	150-1000		252
Copper	5-10	2000-1000		252
Nickel	< 40	350-1000		252
Zinc	10	200-2000		252

TABLE 109. PHYSICAL AND CHEMICAL CHARACTERISTICS OF REFUSE AND SEWAGE SLUDGE SUBSTRATES (253)

Parameter	Refuse	Sewage Sludge
Total Solids, wt %	93.2-97.2	1.7-3.5
Volatile Solids, wt %	76.1-84.9	43.0-47.5*
Total Carbon, wt %	39.8-45.2	20.2*
Total Nitrogen, wt %	0.1-0.8	1.9*
Ammonia Nitrogen, wt %	0.02-0.08	1.4*
Hydrogen, wt %	5.58-5.67	2.9*
Ash, wt %	14.6-15.2	61.1*
pH	7.20-7.30	7.25-7.42
Alkalinity, mg/ℓ $CaCO_3$	173.7-202.0	4120-4525
Heat Content (Dry Basis), Btu/lb	6840-8120	3520

* Weight percent of dry sludge solids.

TABLE 110. EFFLUENT QUALITY AND SOLIDS REDUCTION AT THE OPTIMUM REFUSE DIGESTION TEMPERATURES AND A DETENTION TIME AND LOADING RATE OF 12 DAYS AND 0.14 LB VS/CF-DAY, RESPECTIVELY (253)

	Optimum Digestion Temperatures, °C	
	35	55
Effluent Volatile Acids, mg/ℓ HAc	135	197*
Effluent Soluble COD, mg/ℓ	904	1222
Alkalinity, mg/ℓ $CaCO_3$	3414	6188
pH	7.33	7.10
Ammonia Nitrogen, mg/ℓ N	110	680
Volatile Solids Reduction, %	58.5	69.1

* Note: This concentration does not include unidentified volatile acids which were detected but could not be measured separately. Consequently, the actual volatile acid concentration would be higher than that noted in this table.

operating temperature range. The ammonia nitrogen content is high and, if discharged before being oxidized, could cause problems in a receiving body of water. The second-stage BOD (e.g., the oxygen demand beyond that reported in the BOD_5 determination) is dominated by oxidation of ammonia (NOD) and is probably responsible for the difference in BOD and COD values.

A related fact in this regard is seen by comparing Table 110 with Table 108. It was indicated in Table 108 that for mesophilic digestion (~ 35 C), ammonia nitrogen might reasonably be expected to be in the range of 50-200 ppm for optimum operation. The data in Table 110 confirms this assumption. However, thermophilic concentration exceeds this value by more than a factor of three. This clearly demonstrates that these two process conditions must be evaluated separately, both in terms of the treatability of their output and the expected concentration of heavy metal in effluent liquid and solid streams.

Certain of the digestor feeds such as animal wastes are claimed to produce a solid by-product with value as a fuel, soil conditioner, fertilizer, and animal feed(254). However, each cycle concentrates hazardous materials and cannot eliminate residuals completely.

In summary, it seems apparent that insufficient data exist to completely characterize the residuals from anaerobic digestion of biomass and other waste. Data which ought to be gathered include organic matter, BOD, COD, bacteria and pathogen counts, pH, and sodium in both the aqueous waste and solid residue. Leach tests on the solids under expected environmental conditions should provide data on contaminant mobility potential.

Acid Hydrolysis

The breakdown of cellulosic wastes to fermentable sugars via acid hydrolysis and the subsequent fermentation to ethanol produces both solid and liquid by-products. These include lignin, which comprises the major portion (60-70 percent) of the insoluble residue, plus methanol, acetic acid, furfural, and non-fermentable sugars. The methanol and acetic acid may prove recoverable if commercial-scale production is achieved(255). Uronic acid and other sugar decomposition products are also discharged from the reactor and together with the furfural and non-fermentable sugars represent a high BOD waste stream that would require secondary aerobic biological treatment or perhaps could be land-treated. The feedstock must be diluted in solids for reaction, so large volumes of liquid will need to be treated and recycled to the feed and the system or discharged.

Only one study was located which determined the BOD of the spent liquor. Converse, et al,(256) measured the 5-day BOD of an unfiltered liquor sample as 6,550 ppm and that of a filtered sample as 6,070 ppm. The estimated quantity of effluent was 1,600 gallons per ton of material hydrolyzed (based on a 250 ton/day capacity). An interesting point was noted by these authors, who stated that the presence of ferrous and nitrate ions precluded the use of the standard BOD test. The concentrations were not reported, however.

A large-scale plant would need a secondary treatment facility on the order of that required by a medium-size town of 50,000 to 80,000 people based on organic loads. Furthermore, a BOD reduction efficiency on the order of 98 percent is necessary for an effluent BOD of 100 mg/l. These estimates depend on the process variables and by-product markets, for example the recovery of methanol. The dewatering of the lignin residue may permit use as a solid fuel, since it has a high heating value (10,500 Btu/lb). This would provide volume reduction. On the other hand, carbonization or solvent extraction of the ligneous material may provide new sources of compounds which are presently synthesized from petroleum bases.

The technology of this conversion process has not yet proven sufficiently attractive to warrant in-depth research. As a result, many of the environmental impacts remain unquantified.

ENVIRONMENTAL REVIEW OF SCENARIOS

The regional scenarios developed earlier provide the rationale for the tabular presentation of data on preliminary environmental impacts of biomass collection and conversion. Because many of the systems have not been studied beyond the bench or pilot-plant scale, the emissions and effluent factors are of necessity extrapolations of available information. Data for the tables are taken directly from the text, except in those cases where a particular reference is noted. The express purpose of the scenarios is not to provide final answers, but rather to suggest a methodology and to point out problem areas where further investigation is indicated.

In addition to the expected physical, chemical and ecological impacts, a brief synopsis of the possible socio-economic consequences of biomass is presented. Again, the purpose of the discussion is to point the way for future research efforts.

Environmental Summaries of Scenarios

Capsule summaries of the salient environmental features of the six scenarios developed in Section 6 are presented in Tables 111 through 116. These were prepared to highlight these features and should not be construed as more than an initial accounting of the environmental effects. At some point in future, they should be expanded, with more detailed site and plant data used to characterize the impacts.

Socio-Economic Aspects of Biomass

The implementation of large scale collection, treatment, processing and conversion of biomass materials will alter existing social and

TABLE 111. SCENARIO 1: ENVIRONMENTAL SUMMARY, PYROLYSIS OF WOOD

Pollutants		Quantity
Air Emissions	Particulates	0.6-1.2 kg/MT of wood wastes (3,000-6,000 kg/day for 5,000 MT plant).
	Hydrocarbons, SO_x, NO_x	Small due to nature of source and conversion process.
	Noise	May be locally severe, e.g., near shredders, but most activity will occur in remote areas.
	Organics	Should be negligible.
Water Effluents	BOD/COD	Estimated to be 500-3,000 mg/1 and plant to treat 2,600 MT/day (~ 0.7 MGD) of wastewater. This results in a needed treatment capacity of 1,300-7,800 kg/day or that required for a population of 7,500-40,000.
	Metal Content	Unknown but should be very low.
Solid Residue	BOD/COD	May be high in leachate (and also may be contributed by the material in storage, if not covered properly or enclosed). The quantity estimated to be landfilled will occupy a volume of 3,300-6,600 ft^3/day based on a bulk density of the ash between 50 and 100 lb/ft^3.

TABLE 112. SCENARIO 2: ENVIRONMENTAL SUMMARY FOR ACID HYDROLYSIS OF BAGASSE/FOREST RESIDUES

Pollutants		Quantity
Air Emissions	Particulates	Nil
	Hydrocarbons, SO_x, NO_x	Unknown but expected to be small due to nature of process. Handling of feedstock may cause dusting if partially dried before processing.
	Noise	Locally high, e.g., preprocessing equipment, transportation.
Water Emissions	BOD	6,000 mg/l; discharge of 4.8 MGD (based on 1,600 gal/ton of feed). Resultant loading is 109,000 kg BOD/day or a population equivalent of 96,000.
	Metals	Unknown; should be minimal.
Solid Residue		If solid is landspread, the BOD, suspended solids, and dissolved materials may be spread over a large enough area to eliminate any difficulties. If, however, the disposal is via landfill, the residuals may need to be monitored carefully.

TABLE 113. SCENARIO 3: ENVIRONMENTAL SUMMARY FOR ANAEROBIC DIGESTION OF KELP/MSW

Pollutants		Quantity
Air Emissions	Particulates, NO_x, SO_x, HC	Insignificant due to process/ feed material.
	Odor and Noise	Objectionable at times, especially if "stuck" reactor loads must be disposed of.
Water Effluents	BOD	Estimated volume of .7-.9 MGD (3,000 MT/day) and concentration of 500 mg/1 produces a loading of 1,500 kg/day
	Suspended Solids	3-4 MT/day
Solid Residue		~ 3,100 MT/day spread as fertilizer will require 155 ha/day at an application rate of 20 MT/ha (~ 8 ton/ac). Individual sites may have run-off or ground water contamination problems that will have to be identified by field analysis.

TABLE 114. SCENARIO 4: ENVIRONMENTAL SUMMARY FOR TURBOELECTRIC PEAKING ELECTRICAL GENERATOR WITH FLUIDIZED BED USING ENERGY CROP/CORN RESIDUE

Pollutants		Quantity
Air Emissions	SO_x, NO_x, HC	Very low due to use of fluidized-bed combustor.
	Particulates	Can be reduced to a level equivalent to that experienced with incineration. The small plant capacity (3.6 x 10^9 Btu/da) yields a particulate emission of less than 2,000 kg/da.
Water Effluent		The only water requirements are for cooling system make-up and wash water and should contribute minimal pollutants for this size plant.
Solid Residue		Leachate from spent bed material will be high in suspended and dissolved solids and COD. However, the small quantity of residue should be a mitigating factor.

TABLE 115. SCENARIO 5: ENVIRONMENTAL SUMMARY FOR ANAEROBIC DIGESTION OF ANIMAL WASTE/WHEAT STRAW

Pollutant		Quantity
Air Emissions (similar to those in Scenario #3)	Particulates, NO_x, SO_x, HC	Insignificant due to process/feed material. Dust may be a problem on a local scale if dried wheat straw is pre-processed by shredding.
	Odor and Noise	Objectionable at times, especially if "stuck" reactor loads are disposed of.
Water Effluents (qualitatively similar to those in Scenario #3)	BOD	Estimated volume to be treated daily is 24 MGD (9,240 MT/da) at 500 mg/l BOD. Calculated loading is then 4,620 kg/da. It is conceivable that this waste stream could be land-applied after treatment. It should be free of most hazardous material and could be pumped to nearby fields. Storage periods for feed should be minimized to prevent run-off.
Solid Residue		6,000 MT/da at 50 percent moisture could be land-spread as fertilizer. Careful management and site selection should minimize adverse effects of leaching and maximize soil amendment potential.

TABLE 116. SCENARIO 6: ENVIRONMENTAL SUMMARY FOR DIRECT CONVERSION TO STEAM IN A WATERWALL INCINERATOR USING MSW

Pollutants		Quantity
Air Emissions	Particulates	Based on 0.4 kg particulates per ton refuse burned,(a) emitted by the Chicago incinerator, yields are approximately 2,000 kg/day.
	NO_2	9,000 kg/day based on 3.53 lb/ton of refuse(b).
	SO_2	10,000 kg/day based on 3.94 lb/ton of refuse(b); no scrubber.
	HC	4,000 kg/day based on 1.58 lb/ton of refuse(b).
Water Effluent	BOD/COD	Wash water/cooling water will contribute minor amounts of these pollutants.
	pH	Leachate from ash handling will exhibit pH values in the range 10-12 due to ash composition.
	Dissolved Solids	High due to leachable salts.
	Metals	Should be negligible due to high pH, but will be present in trace amounts.
Solid Residue	BOD/COD	Some will be present due to uncombusted material.
	Metals	Analysis of MSW ash indicates metals are present in the range of 0.05-0.4 wt. percent. However, the small volume of waste and use of landfill liners should minimize the problem.

(a) Hughes, et al., 1974.
(b) Surprenant, et al., 1976.

economic frameworks in the areas served. The analysis of the magnitude of change is beyond the scope of this study. Hence, a brief description of the type of social and economic pressures must suffice.

The two models to be treated are the rural small community type and the urban center type. The parameters that appear to be important are the employment picture, income distribution, alternative allocations of resources, funding sources and public sentiment. The context of this discussion is the regional scenario outlined previously. Projections of expected specific trends for the future should be considered in a separate investigation.

It is expected that, to be economically viable, the processing facilities will have to be located near the growth and/or collection areas. In the scenarios involving animal waste, crop residues, forest residues, and perhaps energy crops, the plant will be a major industry in an otherwise rural area. Judged in terms of available technology, biomass conversion appears to be more labor intensive than fossil fuel recovery. Thus, biomass facilities may provide additional jobs for certain areas. Workers to fill these newly created positions may be available locally where they may have been operating marginally productive farms or small businesses. Alternatively or additionally, labor may be imported from outside the region. The newly generated money flow may induce secondary economic growth in the form of expansion of existing commercial and social services, but may also lead to changes in tax structure required to construct new schools and other public buildings as well as to foster continued public services. Depending on relative pay scales, workers employed in these new positions may skew the income distribution of the community. The possibility of this fact should be investigated.

In fact, the stable and often homogeneous areas likely to be impacted upon by such development may prefer to forego the benefits altogether. Public sentiment may determine that maintenance of the status quo best represents local interests. This in itself may offer opportunities for friction since it is highly unlikely that a consensus will be reached.

The other model type which is identifiable is the urban center. To a limited degree these scenarios have already been implemented in the form of incineration facilities for municipal solid waste. Since the collection system is already developed, social and economic impacts will differ only in degree rather than in type. Studies to isolate the particular groups affected should be conducted but, because of the heterogeneous nature of urban populations, such socio-economic changes may prove minor. Projected facilities are larger than any presently operating. Funding sources and public sentiment regarding construction and operation of such plants should be analyzed before large-scale development proceeds.

One scenario which is difficult to categorize as urban or rural is the ocean farming of kelp. The harvesting and transport operation requires significant manpower and capital inputs. As such, the supply and demand curves for other coastal industries, e.g., commercial fishing, may be affected. The effects of this redistribution of resources and income should be examined in detail. However, if market forces are operating properly, economic efficiency should result.

The preceding outline can in no way substitute for a well researched socio-economic investigation. Such a task could be based on the six regional scenarios or could be defined in any other suitable fashion. In either case, social and economic constraints may be just as important as environmental considerations in the final choice of technology and geographic area. Some consideration should also be given to the longer-range implications of biomass conversion, when the scale of operations may involve millions of acres of land and hundreds of thousands of people.

SECTION 8

CURRENT GOVERNMENT AGENCY EFFORT IN THE BIOMASS PRODUCTION/CONVERSION FIELD

Because of the multiple objectives and broad range of technologies applicable to Biomass-to-Synthetic Fuels systems, government-sponsored research and development is being undertaken by several agencies. Besides the Environmental Protection Agency, other agencies known to be active in the field include the Department of Energy (DOE) (formerly ERDA), the National Science Foundation (NSF), the Department of Agriculture (USDA), the National Aeronautical and Space Administration (NASA), the Department of Defense (Army and Navy), and the Department of the Interior. State and local governments (e.g., state agricultural departments and state environmental protection agencies) are also sponsoring research; the level of effort, however, is believed to be small. In addition to government sponsorship, biomass-related research is also being funded by industrial groups engaged in fuel production, utilization and distribution, notably the Electric Power Research Institute (EPRI) and the American Gas Association (AGA). Finally, several government agencies have more than one organizational element with missions and expertise in biomass systems.

It is beyond the scope of this study to attempt to detail all of the ongoing work relevant to Biomass-to-Synthetic Fuel technology. However, in order to try to recommend areas of research that are technologically relevant and complementary in nature to research projects supported by other agencies, it is necessary to assimilate and categorize the major ongoing efforts conducted by the most relevant agencies. It is believed that most of this effort is concentrated in DOE. The following summary is based on discussions with agency personnel responsible for the specific program areas. Programs described are those which were underway in late 1976.

EPA - WASTE-TO-FUEL PROGRAM

Various offices and divisions within EPA have funded small-scale, pilot, and demonstration programs in the waste-to-fuels areas. These programs span the range of thermochemical and biochemical conversion processes and include substantial efforts in combustion, pyrolysis, and anaerobic digestion activities.

Review of all these programs is beyond the scope of this report. The interested reader is referred to a recent summary article by Huffman(257) for a synopsis of recent efforts. More comprehensive documentation of EPA programs in this area may be found in References (258) and (259).

DOE - OFFICE OF SOLAR, GEOTHERMAL AND ADVANCED ENERGY SYSTEMS

The activities within this DOE office which are focused on biomass production and conversion technology are exclusively within the Solar Energy Division. Three branches of this division conduct studies which are relevant to some segment of this technology. These are the Fuels from Biomass Branch, the Environmental and Resource Studies Branch, and the Agricultural and Process Heat Branch.

The Fuels from Biomass Branch has primary responsibility for the development of biomass production and conversion technology for all biomass sources except urban and industrial waste. The overall objective of this branch is to develop a unified program which will allow biomass energy sources to be developed at a level that meets or exceeds that projected in the ERDA 49(260) document.

The Environmental and Resource Studies Branch is charged with responsibility for identifying the environmental consequences of technology development in all solar energy fields. The technology developments of its sister branch, Fuels from Biomass, are therefore consistent with the mission of this branch.

The Agricultural and Process Heat Branch has responsibility for direct use of solar energy for its thermal capacity. Its mission impinges on biomass production/conversion technology only in the areas where it could be used to dry grains and crops. For this reason, the activities of this branch will not be discussed further.

Solar Energy Division, Fuels from Biomass Branch (FFB)

The work being conducted by the Division of Solar Energy was initiated when this organizational element was part of the National Science Foundation. This initial thrust has continued and accelerated since FFB was incorporated into DOE. As shown in Figure 70(261), the Fuels from Biomass Program has been organized into three program functions with technological thrust and one support function. The time frame for the three programs extends to 1985 and beyond.

For comparison with the definitions used in this report, the agricultural residue projects are concerned with part of the biomass sources reviewed under the heading Forest and Agricultural Waste. The projects on terrestrial biomass incorporate the energy crop and silviculture as well as the forest waste segment of the Forest and Agricultural Waste source. The marine biomass project includes the ocean-based segment of aquaculture. However, reviewing Tables 119 and 120 will show that DOE is also pursuing freshwater biomass production as well.

The urban and solid waste source described earlier in the report is outside the current mission of FFB. However, review of Table 120 will show that some work initiated when this branch was part of NSF was based on a

TABLE 117. AGRICULTURAL RESIDUE PROJECTS*

Project	Program Sub-Element
An Evaluation of the Use of Agricultural Residues as an Energy Feedstock	System Study
Feedlot Energy Reclamation Demonstration	Feedlot Experimental Facility
Methane Fermentation of Feedlot Wastes	Feedlot Experimental Facility
Technological and Economic Assessment of the Utilization of Rice Straw	System Study
Technological and Economic Assessment of Sugar Cane Production Residue	System Study
Technological and Economic Assessment of Methods for Direct Conversion of Agricultural Residues to Usable Energy	System Study

* These are only projects being funded by the Fuels from Biomass Branch of DOE's Solar Energy Division.

solid waste feedstock. Within DOE, major responsibility for this area now resides with the Office of Energy Conservation.

Table 117, which categorizes current FFB projects which have emphasis on agricultural residue, shows that a total of six projects are underway or have been completed. Most projects can be categorized as system studies although the Feedlot Energy Reclamation Demonstration (undertaken by Hamilton Standard) and the Methane Fermentation of Feedlot Wastes (inter-agency agreement with USDA) are actually related to the Feedlot Experiment Facility item in the agricultural residue projects program.

Projects related to conversion of terrestrial biomass are reviewed in Table 118. Four programs have been undertaken in this area, all identifiable as system studies.

Three system studies, shown in Table 119, have been undertaken in the marine biomass area.

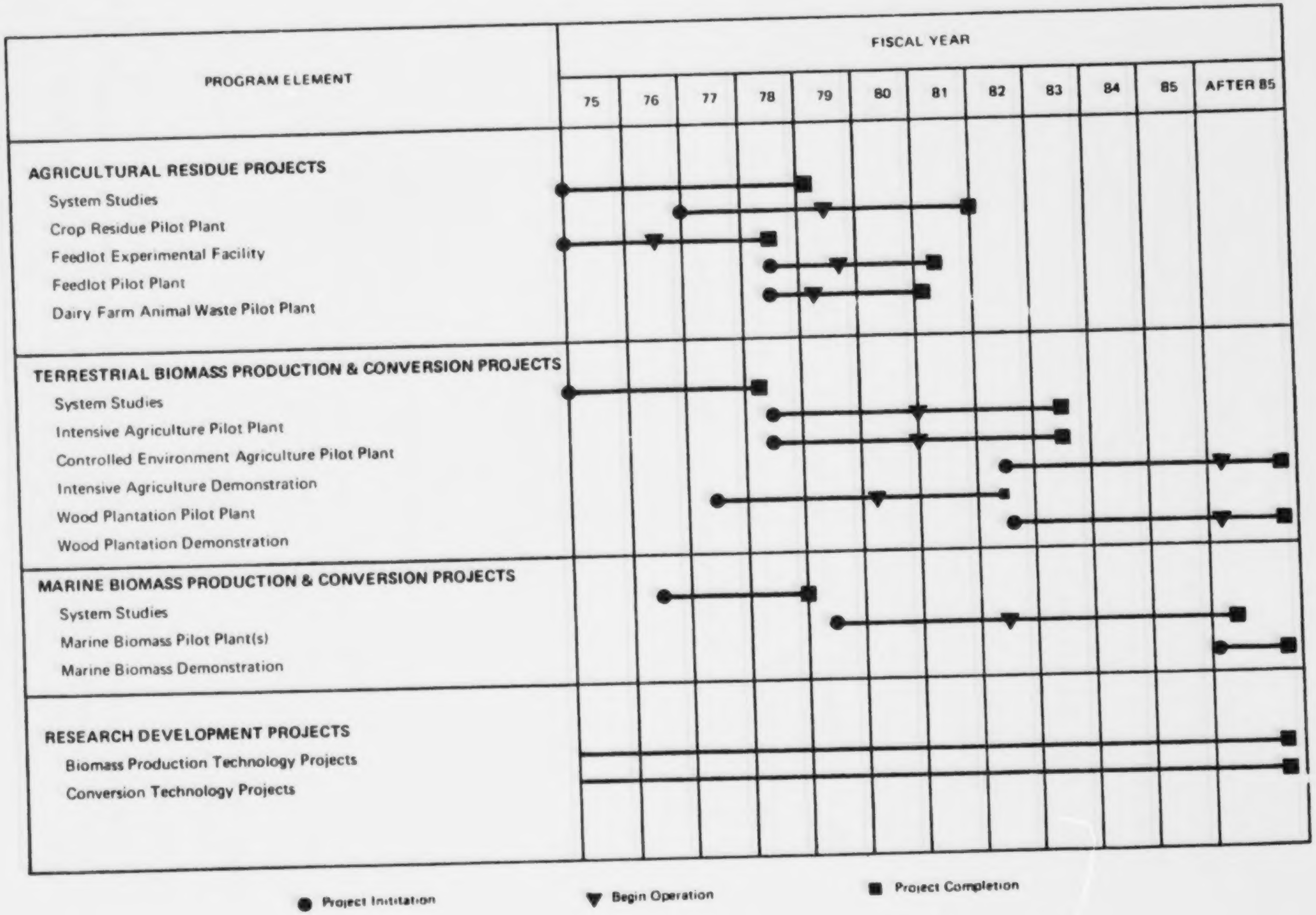


Figure 70. Diagram structure for DOE Fuels from Biomass Branch.(261)

TABLE 118. TERRESTRIAL BIOMASS PRODUCTION AND CONVERSION PROJECTS*

Project	Program Sub-Element
System study of energy concepts based on sugarcane, sweet sorghum, sugar beets, and corn	System study
System study and program plan for silviculture energy plantations	System study
System study of fuels from grains and grasses	System study
Forest industry energy program feasibility study	System study

* These projects are only those funded by the Fuels from Biomass Branch of the DOE Solar Energy Division.

TABLE 119. MARINE BIOMASS PRODUCTION AND CONVERSION PROJECTS*

Project	Program Sub-Element
Evaluating ocean farming of seaweed as sources of organics and energy	System study
Ocean farming for kelp production and harvesting	System study
Marine pastures	System study

* These projects are only those funded by the Fuels from Biomass Branch of DOE's Solar Energy Division.

TABLE 120. RESEARCH/DEVELOPMENT PROJECTS[(a)]

Project	Related Program Element	Project Orientation
Study to determine optimum use of Albany, Oregon, pilot plant for advancement of processes for conversion of cellulosic materials to liquids or gases	1. Terrestrial Biomass	Conversion Process
Technological evaluation of the waste-to-oil pilot plant at Albany, Oregon	2. Terrestrial Biomass	Conversion Process
Pilot plant studies for production of sugars and ethanols based on enzymatic hydrolysis of cellulose	3. Terrestrial Biomass	Conversion Process
Large-scale cultivation of filamentous blue algae in solar bioconversion systems	6. Marine Biomass	Production
Solar energy conversion with hydrogen producing algae	7. Marine Biomass(b)	Conversion Process
Bioconversion of agricultural wastes for energy conservation and pollution control	9. Agricultural Residue	Conversion Process
Construction of wood waste-to-oil facility	4. Terrestrial Biomass	Advanced Process Development
Cultivation of macroscopic marine algae for energy conversion, hydrocolloid production and advanced waste water treatment	8. Marine Biomass	Production
Methane for farm energy	10. Agricultural Residue	Conversion Process
Utilization of woods as chemical raw material	5. Terrestrial Biomass	Conversion Process

TABLE 120. (Continued)

Project	Related Program Element	Orientation
Biological conversion of organic refuse to methane	11. Urban and Industrial Waste (c)	Conversion Process
Heat treatment of refuse for increased anaerobic biodegradability	12. Urban and Industrial Wastes	Conversion Process
Engineering evaluation of program to recover fuel gas from waste	Non-specific	Conversion Process
Combustion of sulfur compounds of sulfur-bearing fuels	Non-specific	Conversion Process

(a) These projects are only those funded by the Fuels from Biomass Branch of DOE's Solar Energy Division.

(b) This program is a freshwater analog to marine studies and so logically fits into the marine biomass element.

(c) These programs were initiated when the Fuels from Biomass Branch was part of NSF and had program interests in this area.

Most of the projects sponsored to date by FFB have been categorized in the research or development category. Reviewing Table 120 will show that five of these projects have been in support of terrestrial biomass, two in support of marine biomass, and two in support of agricultural residue programs.

In addition, two have been related to solid waste sources of biomass, and two were not specific in nature.

Reviewing these research and development projects in the context of their project orientation, conversion processes are overwhelmingly favored over biomass production and related research by an 11 to 2 margin. This emphasis on conversion process development is not illogical since (1) in most cases, the results of the system studies in the biomass area will be required to identify plant species or waste systems on which work should concentrate, and (2) most of the process development work would appear to be directed at processes with broad application in terms of biomass source feedstocks.

Over the short term, the major effort within FFB will be to complete the various system studies currently underway. These will be reviewed by DOE to insure their conclusions are valid. These conclusions will then provide the basis for integrated pilot plants associated with terrestrial and agricultural residue biomass sources.

The system on aquaculture (an expansion from marine biomass projects) will probably lag the completion of other biomass system studies. However, some pilot-scale work will probably precede completion of the system study.

FFB anticipates that the conclusions reached in the various system studies will provide the thrust for initiating work on critical collection, storage, transportation, equipment, development problems. During the past several years, FFB has supported work on single-farm energy conversion systems, primarily through USDA. This thrust does not appear to be growing.

Solar Energy Division, Environmental and Resource Studies Branch (ERSB)

This branch of DOE's Solar Energy Division is currently directing its efforts toward determination of long-term social and environmental consequences of solar energy development as projected in the ERDA 49 plan. Three programs are currently underway that impinge on the biomass-to-synthetics fuels technology.

One of the programs is preparing technology descriptions for each of 8 solar energy technologies, including biomass. These will then be evaluated and the environmental problems associated with each will be identified. These will likely include residuals, ambient impacts, social-economic impacts, and similar data. This study will culminate in a development of detailed environmental studies plan for each of the 8 technologies.

A second study is underway which is taking a very broad look at the social and environmental implications of various solar energy scenarios using the ERDA 49(260) as a data base. This study is designed to work from narrow descriptions of various solar energy technologies and work outward until social, political, economic, and environmental consequences of global significance have been identified. The study will pose very fundamental questions about whether it is possible on a long-term basis to develop a distributed solar energy supply for use in the concentrated industrial societies that are prevalent today.

A third study is underway which is primarily a support study for the other two noted above. One task that has been initiated under this support effort has been to try to quantify the relationship between the environmental implications identified in the previously noted studies and the goals of the National Environmental Policy Act. A second task has sought to evaluate the sensitivity of conclusions made in the previous studies to various assumptions or omissions. A third task, which will probably involve developing a seminar to present the results of these earlier studies, is currently being planned.

In the long-term plan this group is to assess the environmental and social effects of each solar technology being developed as part of and in concert with technological branches of the Solar Energy Division. Over shorter term and in cooperation with the Fuels from Biomass Branch, it is planned to initiate environmental studies of the planned pilot plants.

DOE - OFFICE OF ENERGY CONSERVATION

The Office of Energy Conservation of DOE has the general objective of reducing consumption in the United States by reducing demand and by more fully utilizing available energy sources. One energy source that is underutilized is wastes, and there are two branches within this office with emphasis in this biomass source area. These branches are within two divisions: the Buildings and Community Systems Division and the Industrial Energy Conservation Division.

Building and Community Systems Division, Urban Waste Technology Branch (UWTB)

This branch has become active in developing technology for waste conversion. Table 121 has been constructed to place UWTB projects currently being conducted within the definitions used in this report. There are seven projects underway with thermochemical process orientation and eight projects where the primary emphasis is on biochemical methods. Three studies of a general support nature were identified. Within the thermochemical projects, there is about equal distribution between pyrolysis and direct conversion technologies. One project with a secondary process orientation was identified.

Within the biochemical technology area, there is a strong emphasis on anaerobic digestion, with seven of the eight projects oriented in that direction. Anaerobic digestion is, of course, undoubtedly the biochemical process nearest to commercialization. One project is directed at enzymatic hydrolysis development.

The program emphasis within the group is anticipated to continue along the lines of present program structure, with additional novel commercialization-oriented technologies receiving support as they are identified. In terms of technology emphasis, additional work in combustion systems is expected to be minor. Emphasis in this area will relate to boiler corrosion and probably high pressure/temperature boiler design. Demonstration of a pyrolysis process(es) is anticipated within a relatively short time frame. Gaseous fuel cell and small system development are also likely to receive support.

TABLE 121. SUMMARY OF PROJECTS UNDERWAY BY DOE's URBAN WASTE TECHNOLOGY BRANCH

Thermochemical Systems		Bio-chemical Systems		Support Studies	
Description	Technology	Description	Technology	Description	Technology
Ammonia from Urban Waste	Pyrolysis	Advanced System Experimental Facility	Anaerobic Digestion	Urban Waste Equipment Test and Evaluation Facility	Pre-processing
Chemical Synthesis Gas Production	Pyrolysis	Cellulosic Enzyme Hydrolysis	Enzyme Hydrolysis	Regional Waste System Characterization	General Support
European Waterwall Incinerator Assessment	Direct Conversion	Packed Bed Anaerobic Digestion	Anaerobic Digestion	Development of a Glass-Polymer Composite Sewer Pipe from Waste Glass	Not Fuel Conversion Related
Cofiring MSW in a Cement Kiln	Direct Conversion	Enhanced Anaerobic Digestion	Anaerobic Digestion	----	----
Waste Carbon Monoxide as Natural Gas Replacement in Chemical Feedstocks	Secondary Conversion Process	Anaerobic Digestion of Industrial Wastes	Anaerobic Digestion		
		High-rate Anaerobic Digestion	Anaerobic Digestion	----	----
Home Heating and Cooling Utilizing Wastes	Direct Conversion	Energy and Protein Production from Pulp Mill Wastes	Anaerobic Digestion	----	----
Conversion of Cellulosic and Polymer Wastes to High Octane Gasoline	Pyrolysis	Digestor Mixing Tests	Anaerobic Digestion	----	----

Industrial Energy Conservation Division, Materials Optimization Branch

This recently organized branch has responsibility for the industrial waste utilization functions within the Office of Conservation. While industrial waste utilization is an element of its overall responsibility, primary program emphasis over the longer term will be toward optimizing material flows and process trains to minimize total energy accumulation. This will be accomplished by evaluating the elements of the processing train from the extraction-harvesting stage to consumer distribution functions. Implementative modifications may include the substitution of alternative materials with lower energy use characteristics or modifications in the processing train to decrease energy use. An adjacent program is the research, evaluation and development to commercial scale of new engineering materials as required for specific energy-related applications or as indicated to be needed by the results of the materials optimization analysis.

As related to biomass, the industrial waste utilization opportunities in the food and fiber industry are the most likely candidates for biomass source materials. This branch will limit its interest to the waste available at manufacturing sites, leaving to the Fuels from Biomass Branch the consideration or production site waste utilization functions. Waste conversion technology will apparently not receive major emphasis in this group, with only very novel process systems being considered for support.

This branch also coordinates all modeling and systems analytic efforts within the Division of Industrial Energy Conservation.

DOE - OFFICE OF ENVIRONMENT AND SAFETY

This office provides support to the DOE technology offices in the areas of environmental control and containment requirements, and in health-related topics. The programs of two divisions, Environmental Control Technology and Biomedical and Environmental Research, are expected to have impact on biomass production/conversion technology.

DOE, Division of Biomedical and Environmental Research

This division's current program impinges on biomass conversion technology in only a single program. The division is supporting, in cooperation with EPA, the Ames-Iowa combined firing project. The activities for DOE are being carried out by DOE's Ames Laboratory. DOE's effort has included baseline studies on the characterization of particle size throughout the process as well as characterization of stack emission with respect to trace element content of particulates, SO_2, NO_x, and organics. There are also ongoing studies on microbiological agents present in stored solid waste.

Immediate plans of this division are to develop a cooperative effort with EPA on the environmental evaluation of the Pompano Beach anaerobic digestion facility.

DOE, Environmental Control Technology Division

This division of DOE has responsibility for making independent environmental assessments of technological development and programs developed in other DOE divisions. It is not involved in control technology development, and the division's activities generally take the form of paper studies or empirical measurements of environmental emissions. The results of these studies often take the form of recommendations of control technology development which may be developed within (primarily, conversion process modification) or outside the agency.

Given the mission of this division, their involvement in biomass-related activities is anticipated to come primarily in support of technology-development organizational elements.

UNITED STATES DEPARTMENT OF AGRICULTURE

The USDA is clearly an agency with much expertise in the area of biomass cultivation, species mutation, and agricultural/forestry management. Two groups with USDA, the Fuels from Biomass Group and the Forestry Service, presently have programs mobilized. There are probably other groups working in the area that were not identified.

Fuels from Biomass Group, Beltsville Agricultural Center

This group at USDA is conducting three projects, with funds provided by NSF and FEA. One of these studies is on bagasse utilization, a second on anaerobic digestion of beef manure, and a third on utilization of rice straw produced on a 450,000-500,000 acre farm in California.

All of these studies are directed at biomass conversion for the purposes of making single farms less energy-dependent and approaching energy self-sufficiency.

This group supports the concept that collection and harvesting technology need to be emphasized early in biomass technology development in order for complete system efficiency to be developed. Likewise, they feel an intensive effort aimed at improving species for total biomass and food production should be emphasized.

Forest Service, Forestry Research

The USDA organization has an interest in biomass technology by virtue of their general expertise in forest management. ERDA's Fuel from Biomass program has funded work in two research areas. An effort is underway to simulate the harvesting and transport function involved in forest residue use. Previously, a feasibility study was prepared on recovery of methanol, ethanol, furfural, and similar compounds from wood products and residue. The latter work was funded from the Fuel from Biomass group while this was part of NSF and in cooperation with FEA. In addition to ERDA-funded work, USDA is currently conducting a study at Rhinelander, Wisconsin, on the extensive cultivation of fast-growing hardwood which will sprout from stumps and can be harvested every 6-7 years.

Expansion of the work currently underway is the anticipated course of future work.

NATIONAL SCIENCE FOUNDATION

The utilization of biomass for both fuels and other purposes was initiated within the National Science Foundation in its program on Research Applied to National Needs (RANN). The Fuels from Biomass segment of this effort was transferred to ERDA when ERDA was organized in 1975. However, there remains an effort within the National Science Foundation on the use of biomass as raw material for producing non-fuel commodities.

The RANN program is viewed as bridging the gap between basic and applied science. Work on biomass conversion to other resources is primarily conducted by the Advanced Energy and Resources Research and Technology Division (AERRT). The primary resources of current interest are in foods, chemicals, and fertilizers. No work is currently underway in building materials; however, this resource will also eventually be considered.

The structure of the program contains three elements. One of these is on nonrenewable resources and is primarily directed at the mineral market and consequently is of no interest in this study. A second element is directed at resource systems and the work in this element is directed at determining the interrelationship of social, technical, and economic inputs into general resource systems. The renewable resources element has the purpose of developing biomass conversion/production technology and relating these developments to the activities of other federal agencies. The program has three major objectives: (1) to assess alternatives for effective use of biomass, (2) to improve land productivity by evaluating and identifying alternative practices, and (3) to increase the capability to produce protein from non-conventional sources. Each of these objectives has associated with it a program sub-element. Biomass utilization is one of these areas. Most of the emphasis has been toward lignin-research, primarily because this is an area that has been neglected by others. Both biological and chemical systems are of interest. A second sub-element area is that of innovative resources. Biophotolysis (in cooperation with a DOE effort) will be supported under this technology. Also within this area is the research on the mechanism and utilization of biological fixation of nitrogen. The third sub-element is that of photosynthesis research with the emphasis on improving biomass production. Projects related to biomass utilization and supported by NSF/AERRT are:

- Bioconversion of lignocellulosics
- Conversion of lignocellulose by thermophylic actinomycetes microorganisms
- The isolation of lignin-degrading tropical microorganisms

- Enzymatic transformation of lignin
- Enzymatic decomposition of lignin and cellobiose in relation to hydrolysis of cellulose
- Pyrolytic conversion of cellulosic materials.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

There are at least two groups within NASA who are conducting or who have conducted work related to biomass utilization. The Urban Systems Office at NASA's Johnson Space Center has for several years been involved in the Multiple Integrated Utility System (MIUS) program. This program sought to develop housing systems, either at the individual or, more likely, at the housing development level, which were completely independent of outside needs for conventional utilities, including electricity, gas, sewage, urban waste collection, etc. The basis for this work was NASA's manned spacecraft expertise. At one point several years ago, studies were planned to develop both pyrolysis and anaerobic digestion systems scaled down to these very small levels. These studies were never executed, and NASA's involvement has been steadily decreasing. As the work has approached demonstration scale, the effort has been transferred to HUD and the National Bureau of Standards. Their involvement is reviewed later in the report.

NASA'a National Space Technology Labs at Bay St. Louis, Mississippi, has been developing technology for the use of water hyacinths (Eichhornia crassipes) as a tertiary waste water treatment system. Part of the concept involves converting the water hyacinth's plant tissue into anaerobic digestion gas, animal feed, or fertilizer. Batch studies on anaerobic fermentation to produce gas have been undertaken as have crop yield studies to ascertain fertilizer value. Project personnel can see wide application as a tertiary treatment technique in the tropical and semi-tropical climates. Several small communities near the Bay St. Louis laboratory intend to install the system and use the plant tissue for fertilizer after suitable composting. Disney World in Florida is also apparently considering installing a treatment system and developing an associated anaerobic system. Related research work has been conducted on solar drying of the plant tissue and on animal feeding. The plans for the project, which is entirely supported by NASA, are to continue along current program lines for the immediate future.

HUD, OFFICE OF POLICY DEVELOPMENT AND RESEARCH, DIVISION OF BUILDING TECHNOLOGY

This division of HUD, with the direct support of the Department of Commerce, National Bureau of Standard, is making an effort to demonstrate the value of multiple integrated utility systems (MIUS) as a total package for community growth. Their effort has taken the form of one demonstration project (total energy supply only) which began operation in the second quarter of 1976 and a second project which has just entered the design phase.

The first project, which has been implemented in a redevelopment area of Jersey City, New Jersey, is directed at supplying the total energy requirement for 486 dwelling units as well as 250,000 square feet of commercial property. The system was primarily designed to demonstrate reliability and maintainability of these systems and operates unattended except for custodial and emergency support. The complete instrumentation for monitoring demand and modulating supply is in place and operational. Since only the demand side is being demonstrated, no use of solid and liquid wastes has been made. This demonstration will be undertaken in a second project described below.

The second project has been initiated with a private developer in St. Charles, Maryland, and is in the design phase. This system is designed to supply the needs of the equivalent of 1,000 dwelling units, with a dwelling unit rated at 8,000 square feet. Approximately 740 actual individual dwelling units will be utilized, with the balance of the equivalency coming from public/commercial installations such as schools, drug stores, churches, gasoline stations, etc. However, in this system also, reliability has been emphasized and only equipment which are articles of commerce will be utilized.

DOE's Building and Community Systems Division is supporting some research work directed towards improvement of state-of-the-art of systems developed for MIUS application. EPA, NASA, DOD, and other government agencies are apparently members of an advisory panel to aid in MIUS development. A continuing and expanded demonstration program is the likely future direction.

REFERENCES

1. Anderson, L. L. Energy Potential From Organic Wastes: A Review of the Quantities and Sources. U.S. Dept. of Interior, Bureau of Mines Information Circular 8549, Washington, D.C. 16 pages. 1972.

2. Hall, E. H., C. M. Allen, D. A. Ball, J. E. Burch, H. N. Conkle, W. T. Lawhon, T. J. Thomas, and G. R. Smithson Jr. Final Report on Comparison of Fossil and Wood Fuels to the United States Environmental Protection Agency, Battelle-Columbus Laboratories, Columbus, Ohio. 238 pages. 1975.

3. Chappell, T. W. and R. C. Beltz. Southern Logging Residues: An Opportunity. Journal of Forestry 71:688-691. 1973.

4. Grantham, J. B. and T. H. Ellis. Potentials of Wood For Producing Energy. Journal of Forestry 72:552-556. 1974.

5. Jemison, G. M. and M. S. Lowden. Management and Research Implications. pp. A1-A12 in Environmental Effects of Forest Residues Management in the Pacific Northwest: A State-of-Knowledge Compendium. O. P. Cramer (ed.). USDA Forest Service General Technical Report PNW-24, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon. Various Paging. 1974.

6. United States Department of Agriculture Forest Service. The Outlook for Timber in the United States. Forest Resource Report No. 20. Washington, D.C. 367 pages. 1973.

7. Host, J. R. and D. P. Lowery. Potentialities For Using Bark to Generate Steam Power in Western Montana. Forest Products Journal 20 (2): 35-36. 1970.

8. Vranizan, J. M. Utilizing Wood Waste to Offset Plywood Plant Energy Demands. Modern Plywood Technology 1:109-122. 1975.

9. Grantham, J. B., E. M. Estep, J. M. Pierovich, H. Tarkow, and T. C. Adams. Energy and Raw Material Potentials of Wood Residue in the Pacific Coast States - A Summary of a Preliminary Feasibility Investigation. USDA Forest Service General Technical Report PNW-18, Pacific Northwest Range and Experiment Station, Portland, Oregon. 37 pages. 1974.

10. Stephens, G. R. and G. H. Heichel. Agricultural and Forest Products as Sources of Cellulose. pp. 27-42 in Cellulose as a Chemical and Energy Resource. C. R. Wilke (ed.). Interscience Publications, John Wiley and Sons, New York. 361 pages. 1975.

11. Resch, H. The Physical Energy Potential of Wood. Paper Presented at the 65th Pacific Logging Congress, November, 1974, Reno, Nevada. 5 pages. 1975.

12. Koch, P. and Mullen, J. F. Bark From Southern Pine May Find Use as a Fuel. Forest Industries 98(4):36-37. 1971.

13. Martin, R. E. and A. P. Brackebusch. Fire Hazard and Conflagration Prevention. pp. G1-G30 in Environmental Effects of Forest Residues Management in the Pacific Northwest: A State-of-Knowledge Compendium. O. P. Cramer (ed.). USDA Forest Service General Technical Report PNW-24, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon. Various paging. 1974.

14. Loehr, R. C. Agricultural Waste Management: Problems, Processes, and Approaches. Academic Press, New York. 576 pages. 1974.

15. Humphrey, A. E. Economical Factors in the Assessment of Various Cellulosic Substances as Chemical and Energy Resources. pp. 49-66 in Cellulose as A Chemical and Energy Resource. C. R. Wilke (ed.). Interscience Publications, John Wiley and Sons, New York. 361 pages. 1975.

16. Tamplin, A. R. Solar Energy: How Shall We Use the Sunlight? Let us Count the Ways. Environment 15(5):16-34. 1973.

17. Wells, D. M., G. A. Whetstone, and R. M. Sweazy. Manure, How it Works. Paper Presented at the American National Cattlemen's Association/Environmental Protection Agency Action Conference, August 28-29, 1973, Denver, Colorado. 1973.

18. Coe, W. B., and M. Turk. Processing Animal Waste By Anaerobic Fermentation. pp. 29-37 in Symposium: Processing Agricultural and Municipal Wastes. G. E. Inglett (ed.), Avi Publishing Company, Westport, Conn. 221 pages. 1973.

19. Halligan, J. E., K. L. Herzog, H. W. Parker, and R. M. Sweazy. Conversion of Cattle Feedlot Wastes to Ammonia Synthesis Gas. Environmental Protection Technology Series EPA-660/2-74-090, United States EPA, Corvallis, Oregon. 46 pages. 1974.

20. Milne, C. M. State of the Art: Methane Gas Generation From Agricultural Wastes. Montana State University Cooperative Extension Service and Agricultural Experiment Station Folder No. 160, Bozeman, Montana. 7 pages. 1974.

21. Klass, D. L. Wastes and Biomass as Energy Resources: An Overview. pp. 21-58 in Clean Fuels From Biomass, Sewage, Urban Refuse, and Agricultural Wastes. Institute of Gas Technology, Chicago. 459 pages. 1976.

22. Douglas, R. W. Synthetic Natural Gas From Animal Wastes by Anaerobic Fermentation. pp. 183-196 in Clean Fuels From Biomass, Sewage, Urban Refuse, and Agricultural Wastes. Institute of Gas Technology, Chicago. 459 pages. 1976.

23. Wong-Chong, G. M. Dry Anaerobic Digestion. pp. 361-372 in Energy, Agriculture, and Waste Management. W. J. Jewell (ed.). Ann Arbor Science, Ann Arbor, Michigan. 540 pages. 1975.

24. United States Department of Agriculture. Agricultural Statistics: 1975. United States Government Printing Office, Washington. 621 pages. 1975.

25. National Academy of Sciences. Atlas of Nutritional Data on United States and Canadian Feeds. Washington, D.C. 772 pages. 1972.

26. Miller, D. L. Nonwood Cellulosic Raw Materials. Chapter 8 in New Resources From the Sun. Proceedings of the 34th Annual Conference of the Chemergic Council, Washington, D.C., November 1-2, 1973. Various paging. 1973.

27. Szego, G. C. and C. C. Kemp. Energy Plantations. Chapter 3 in New Resources From the Sun. Proceedings of the 34th Annual Conference of the Chemergic Council, Washington, D.C., November 1-2, 1973. Various paging.

28. Alich, J. A. Jr., and Inman, R. E. Effective Utilization of Solar Energy to Produce Clean Fuel. Report to National Science Foundation, NSF/RANN/SE/GI 38723/FR/74/2, Stanford Research Institute, Menlo Park, California. 161 pages. 1974.

29. Klass, D. L. A Perpetual Methane Economy-Is It Possible? Chemtech 4:161-168. 1974.

30. Schlesinger, M. D., W. S. Sanner, and D. E. Wolfson. Energy From The Pyrolysis of Agricultural Wastes. pp. 93-100 in Symposium Processing Agricultural and Municipal Wastes. G. E. Inglett (ed.). Avi Publishing Company, Westport, Connecticut. 221 pages. 1973.

31. Meade, G. P. Cane Sugar Handbook. 9th Ed. John Wiley and Sons, New York, 1963. 845 pages. 1963.

32. Illinois Department of Agriculture and United States Department of Agriculture. Corn and Soybean Harvesting, Handling, and Drying Methods, 1975 With Comparisons. Bulletin 76-2, Illinois Cooperative Crop Reporting Service, Springfield, Illinois. 10 pages. 1976.

33. Lieth, H. Primary Productivity in Ecosystems: Comparative Analysis of Global Patterns. pp. 67-88 in Unifying Concepts in Ecology W. H. van Dolben and R. H. Lowe-McConnell (eds). Dr. W. Junk, The Hague, 1975.

34. Louisiana Wildlife and Fisheries Commission, Thirteenth Biennial Report, New Orleans, Louisiana. 1968-1969. 156 pp.

35. Odum, E. P. Fundamentals of Ecology. W. B. Saunders, Co., Philadelphia. 1971. pp. 574.

36. Keefe, C. W. Marsh Production: A Summary of the Literature. Contrib. Marine Science 16:163-180. 1972.

37. Alexander, M. Introduction to Soil Microbiology. J. Wiley and Sons, Inc. 1961.

38. Pomeroy, L. R. Algal Productivity in Salt Marshes of Georgia. Limnol. Oceangr. 4:386-397. 1959.

39. Harper, R. M. Some Dynamic Studies of Long Island Vegetation. Plant World 21:38-46. 1918.

40. Seidel, K. Scripus-Kulturer. Arch. Hydrobiol. (Plankt.) 56:58-92. 1959.

41. Jervis, R. A. Primary Production in a Freshwater Marsh Ecosystem. Ph.D. Thesis Rutgers University. 1964.

42. Woodhouse, Jr., W. W., E. D. Seneca, and S. W. Broome. Propogation of Spartina alterniflora for Substrate Stabilization and Salt Marsh Development. Fort Belvoir, Va., U.S. Coastal Engineering Research Center TM-46. 1974. 155 pp.

43. Willingham, C. A., B. W. Cornaby, and D. G. Engstrom. A Study of Selected Coastal Zone Ecosystems in Relation to Gas Pipelining Activities Final Report to Offshore Pipeline Committee, Houston, Texas. Battelle, Columbus Laboratories, Columbus, Ohio. 1975. 200+ pp.

44. Penfound, W. T. and T. T. Earle. The Biology of the Water Hyacinth. Ecol. Monogr. 1948. 18:447-478.

45. Westlake, D. F. Comparisons of Plant Productivity. Biol. Rev. 1963. 38:385-425.

46. Boyd, C. E., and R. D. Blackburn. Seasonal Changes in the Proximate Composition of Some Common Aquatic Weeds. Hyacinth Control Journal. 1970. 8:42-44.

47. Parra, J. V. and C. C. Mortenstine. Plant Nutritional Content of Some Florida Water Hyacinths and Response by Pearl Millet to Incorporation of Water Hyacinth in Three Soil Types. Hyacinth Control Journal. 1974. 13:59-61.

48. Goldman, J. C., J. H. Ryther, and L. D. Williams. Mass Production of Marine Algae in Outdoor Cultures. 1975. Nature 254:594-595.

49. McGarry, M. and C. Tongkasome. Water Reclamation and Algae Harvesting. J. Water Poll. Control Fed. 43: 1971.

50. Leese, T. M. The Conversion of Ocean Farm Kelp to Methane and Other Products. pp. 253-266 in Symposium Papers Clean Fuels Orlando, Florida. January 27-30, 1976. Institute of Gas Technology. 1976.

51. U.S. Department of Commerce. 1974. Seaweed forms would pay, says Sea Grant Biologist. Commerce News, NDAA: 74-174, 4 p.

52. Dykyjova, D. 1971. Productivity and solar energy conversion in reed swamp stands in comparison with outdoor mass cultural of algae in the temperate climate of Central Europe. Photosynthetica 5:329-340.

53. Szetella, E. J., N. L. Kroscella, and W. A. Blecher. 1974. Technology for Conversion of Solar Energy to Fuel. Mariculture Investigation: Ocean Forming and Fuel Production. United Aircraft Research Laboratory. East Hartford, Conn.

54. Herbert, L. P., and E. R. Dire. 1972. Long term testing of sugarcane varieties in southern Florida. USDA Agr. Res. Serv. 34-131. 6 p.

55. Agricultural Stabilization and Conservation Service. 1974. Annual Report. USDA, ASCS, Alexandria, Louisiana. 66 p.

56. Burr, G. O., C. E. Hart, H. W. Brodie, T. Tanimats, H. P. Takahashi, F. M. Ashton, and R. E. Coburn. 1957. The sugarcane plant. Ann. Rev. Plant Physiol. 8:275-308.

57. U.S. Department of Agriculture. 1976. Crop Production, 1975 Annual Summary. Crop reporting board, statistical reporting service crPr 2-1(76). Washington, D.C.

58. Loomis, R. S., A. Ulrich, and N. Terry. 1971. Environmental Factors. pp 19-48. Advances in Sugar Beet Production: Principles and Practice. (R. T. Johnson et al (ed.).) Iowa University Press. Ames, Iowa.

59. Hills, T. J., and A. Ulrich. 1971. Nitrogen Nutrition. p. 15. Advances in Sugar Beet Production: Principles and Practice. R. T. Johnson et al (ed.). Iowa University Press, Ames, Iowa.

60. Ribe, John H. 1974. A review of short rotation forestry with comments on the prospect of meeting future demands for forest products. University of Maine at Orono, Life Sciences and Agricultural Experiment Station. Misc. Rpt. 160. 52 pages.

61. Steinbeck, K., R. G. McAlpine, and J. T. May. 1972. Short rotation culture of Sycamore: a status report. Journal of Forestry 70:210-213.

62. Zavitkowski, J. and R. D. Stevens. 1972. Primary Productivity of Red Alder Ecosystem. Ecology 53:235-242.

63. Art, H. W., and P. L. Marks. 1971. A summary table of biomass and net annual primary productivity in forest ecosystems of the world. pp 2-32. In Forest Biomass Studies. XVth I.U.F.R.O. Congress, Gainsville, Florida, March 15-20, 1971.

64. Whittaker, Robert H. 1975. Communities and ecosystems, 2nd ed. Macmillan Publishing Co., Inc., New York. 388 pages.

65. Fowells, H. A. 1965. Silvics of Forest Trees of the United States. U.S. Department of Agriculture, Forest Service, Division of Timber Management Research. Agriculture Handbook No. 271. 762 pages.

66. Forbes, Reginald D., ed. 1955. Forestry Handbook. Ronald Press Co., New York, New York. Various paging.

67. Harlow, W. M., and E. H. Harror. 1958. Textbook of Dendrology. McGraw-Hill Book Co., Inc., New York. 561 pages.

68. Funk, David T. 1973. Growth and development of alder plantings in Ohio strip-mine banks. pp 483-523 in Ecology and reclamation of devestated land. R. J. Hutnik and Grant Davis (ed.). Gordon and Breach, New York. 538 pages.

69. Nelson, Robert E. 1965. A record of forest plantings in Hawaii. U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. Berkely, California. Resource Bull. PSW-1. 18 pages.

70. Rose, Dietmar W. 1975. Fuel forest versus strip mining: fuel production alternatives. J. of Forestry 73:489-493.

71. U.S. Department of Commerce. 1972. 1969 Census of Agriculture. Various parts and sections.

72. Niessen, W. R. and S. H. Chansky. 1970. The Nature of Refuse. Proc. 1970. National Incineration Conf. Amer. Soc. Mech. Eng. N.Y.

73. National Academy of Sciences, 1975. Mineral Resource and the Environment, Supplementary Report: Resource Recovery from Municipal Solid Wastes. National Academy of Sciences, Washington, D.C. 416 pp.

74. Klass, D. L. 1976. Wastes and Biomass as Energy Resources: An Overview. pp. 21-58. In Symposium Papers Clean Fuels. Orlando, Florida. January 27-30, 1976. Institute of Gas Technology.

75. Smith, F. A. 1976. Quantity and Composition of Post-Consumer Solid Waste: Material Flow Estimates for 1973 and Baseline Future Projections. Waste Age 7:2, 6-10.

76. Decision-makers Guide in Solid Waste Management. 1974. U.S. Environmental Protection Agency, Washington, D.C. 157 pp.

77. Decision-makers Workbook: Resource Recovery from Solid Waste. 1975. Dept. Ecology, State of Washington, Seattle. Various pagination.

78. Anonymous, 1976. Shredding cuts space requirements by 70%. Solid Waste Management/RRRJ :32-36.

79. Drobny, N. L., H. E. Hull, and R. F. Testin, 1971. Recovery and utilization of municipal solid waste. Environmental Protection Agency Report SW-10c.

80. Shelton, H. J., 1972. Machines for preparing waste for composting, recycling and resource recovery. Compost Science :22-24.

81. Franconeri, P., 1976. How to select a shredder. Sanitation Industry Yearbook :74-106.

82. Bagnall, L. O., J. F. Hentges, and R. L. Shirley, 1973. Aquatic weed utilization - harvesting and processing. Weed Science Society of America Meeting, Atlanta, Georgia.

83. Arella, D. G., 1974. Recovering resources from solid waste using wet-processing. Environmental Protection Agency Report SW-47d.

84. Huang, C. J. and C. Dalton, 1975. Energy recovery from solid waste. National Aeronautics and Space Administration Report NASA CR-2526.

85. Wilson, D. G., 1975. An excerpted review of advanced solid-waste processing technology. Compost Science :28-32.

86. Savage, G. and G. J. Trezek, 1976. Screening shredded municipal solid waste. Compost Science :7-11.

87. Wise, D. L., S. E. Sadek, R. L. Wentworth and R. G. Kispert, 1974. Fuel gas production from solid waste. Semi-annual progress report. National Science Foundation Report NSF/RANN/SE/C-827/PR/72/4.

88. Sheng, H. P. and H. Alter, 1975. Energy recovery from municipal solid waste and method of comparing refuse-derived fuels. Resource Recovery and Conservation 1:85-93.

89. Millett, M. E., A. J. Baker and L. D. Satter, 1975. Pretreatment to enhance chemical, enzymatic, and microbiological attack of cellulosic materials. Biotechnol. and Bioeng. Symp. No. 5, 193-219.

90. Nystrom, J., 1975. Discussion of "Pretreatments to enhance enzymatic and microbiological attack on cellulosic materials." Biotechnol. and Bioeng. Symp. No. 5, 221-224.

91. Anonymous, "From Oil to Wood Chips", Mechanical Engineering, (April, 1976).

92. Hall, E H. et al, "Comparison of Fossil and Wood Fuels", Final Report from Battelle Columbus Laboratories to the Environmental Protection Agency. Contract No. 68-02-1323, March, 1976. EPA-600/2-76-056.

93. Lorenzi, Otto de, Combustion Engineering, First Edition, Combustion Engineering-Superheater, Inc., New York, Chapter 12, pp 28 (1949).

94. Babcock and Wilcox, Steam, Thirty-Eighth Edition, Babcock and Wilcox, Chapter 27, pp 2-4 (1972).

95. Corder, S. E., "Wood and Bark as Fuel", Research Bulletin 14, Oregon State University, School of Forestry (August, 1973).

96. Fryling, G. R., "Combustion Engineering", Combustion Engineering (1966).

97. Kazmerski, E. A., "Steam Generators for Multiple Fuel Firing", TAPPI, Vol. 42, No. 4, pp 333-336 (April, 1959).

98. "Steam, Its Generation and Use", The Babcock & Wilcox Company, 37th Edition (1963).

99. Prakash, C. B., and Murray, F. E., "A Review on Wood Waste Burning", Technical Paper T170, Canadian Pulp and Paper Association, Pulp and Paper Magazine of Canada, Vol. 23, No. 7 (July, 1972).

100. Miller, E. G., and Hansen, G. E., "Spreader Stoker Firing of Wood and Coal in Multiple Fuel Furnaces", paper presented at the Fifth Annual National Meeting of the Forest Products Research Society (May 1951).

101. Roberson, J. E., "Bark Burning Methods", TAPPI, Vol. 51, No. 6 (June, 1968).

102. Drobny, N. L., Hull, H. E., and Testin, R. F., "Recovery and Utilization of Municipal Solid Waste", Report from Battelle Memorial Institute to Environmental Protection Agency, 1971, pp 66-80.

103. Huang, C.J., "Energy Recovery From Solid Waste - Volume 2", prepared for Lyndon B. Johnson Space Center, NASA, April, 1975.

104. Jackson, Frederick, Energy From Solid Waste. Noyes Data Corporation, Park Ridge, New Jersey, 1974, Chapter 1.

105. Final Report prepared for Council on Environmental Quality, "Resource Recovery", by The Midwest Research Institute, February, 1973.

106. Willson, R. T., "Urban Refuse: New Source for Energy and Steel, Professional Engineer, November, 1974.

107. Wise, D. L. et al, "Fuel Gas Production From Solid Waste", Paper presented at National Science Foundation Special Service on Cellulose as a Chemical and Energy Resource, Berkeley, California, June 25-27, 1974.

108. Levy, Steven, J., "Pyrolysis of Municipal Solid Waste", Waste Age (1974).

109. Bechtel Corporation, "Fuels from Municipal Refuse for Utilities: Technology Assessment", prepared for EPRI (March, 1975).

110. Huang, C. J., et al, "Energy Recovery from Solid Waste, Volume 2 - Technical Report", prepared for NASA, Contract No. CR-2526 (April, 1975).

111. Kuester, James, L., and Lutes, Loren, "Fuel and Feedstock from Refuse", Environmental Science and Technology, Volume 10 (4) (April, 1976).

112. McIntyre, A. D., and Papic, M. M., "Pyrolysis of Municipal Solid Waste", The Canadian Journal of Chemical Engineering, Volume 52 (April, 1974).

113. Schlesinger, M. D., Sanner, W. S., and Wolfson, D. E., "Pyrolysis of Waste Materials from Urban and Rural Sources", proceedings of Third Mineral Waste Utilization Symposium, Chicago, Illinois, pp 424-428 (March 14-16, 1972).

114. Finney, C. S., and Garrett, D. E., "The Flash Pyrolysis of Solid Wastes", Energy Sources, Volume 1 (3), Crane, Russak & Company Publishers (1974).

115. Hammand, V. L., et al., "Energy from Solid Waste by Pyrolysis-Incineration", paper presented at Annual Meeting of Air Pollution Control Association, Eugene, Oregon (November 15-17, 1972).

116. Union Carbide literature on the Purox Process.

117. Tatom, J. W., et al., "A Mobile Pyrolytic System for Conversion of Agricultural and Forestry Wastes into Clean Fuels", Abstract of experiments conducted at Georgia Institute of Technology (1975).

118. Sussman, David, B., "Baltimore Demonstrates Gas Pyrolysis", first interim report prepared for U.S. Environmental Protection Agency, Grant No. S-801533 (1975).

119. Bailie, Richard, C., "Municipal Solid Waste Pyrolysis", reprint of paper presented at 66th Annual Meeting of American Institute of Chemical Engineers (November 11-17, 1973).

120. Garner, William, and Smith, Ivan, C., "The Disposal of Cattle Feedlot Wastes by Pyrolysis", report prepared for the U.S. Environmental Protection Agency, Contract No. 14-12-850 (January, 1973).

121. Beckman, J. A., and Laman, J. R., "Destructive Distillation of Used Tires", proceedings of National Industrial Solid Waste Management Conference, pp 388-392 (March 24-26, 1970).

122. Underkofler, L. A., Hickey, R. J., *Industrial Fermentations*, First Edition, Chemical Publishing Company, New York, New York, 1954, Chapter 5, pp. 137-156.

123. Shreve, N. R., *Chemical Process Industries*, Third Edition, McGraw-Hill Book Company, New York, New York, 1967, pp. 627.

124. Harris, E. E., Beglinger, E., "Madison Wood Sugar Process", Industrial and Engineering Chemistry, Vol. 38 (9), 1946, pp. 890-895.

125. Harris, E. E., et al., "Hydrolysis of Wood", Industrial and Engineering Chemistry, Vol. 37 (1), 1945, pp. 12-33.

126. Harris, E. E., *Advances in Carbohydrate Chemistry*, Vol. 4, Academic Press Publishing Company, New York, New York, 1949, pp. 153-188.

127. Reese, E. T., Mandels, M., Weiss, A. H., *Advances in Biochemical Engineering 2*. Springer-Verlog, New York, New York, 1972, pp. 182-195.

128. Converse, A. O., Grethlein, H. E., Karadikar, S., Kahrtz, S., "Acid Hydrolysis of Cellulose in Refuse to Sugar and its Fermentation to Alcohol", report prepared for the Environmental Protection Agency, Grant No. EP-00279, June, 1973.

129. Draft report to the Energy Research and Development Administration, "Study to Determine Optional Use of Albany, Oregon, Pilot Plant for Advancement of Processes for Conversion of Cellulisic Materials to Liquids", from Battelle Pacific Northwest Laboratories, 1975.

130. Final report to the National Science Foundation, "The Technical and Economic Desirability of Waste-to-Oil Liquefaction Processes", by the Bechtel Corporation, June, 1975.

131. Y. C. Fu, E. G. Ilbig, and S. J. Melia, "Conversion of Manure to Oil by Catalytic Hydrotreating", Environmental Science and Technology, 8, 737-770, 1974.

132. Wastler, T. A., Daugherty, P. M., "Bulletins 19 and 20, State Engineering Experiment Station", Georgia Institute of Technology, Vol. II, No. 1, 1954.

133. Rieck, H. G., Locke, E. G., and Tower, E., "Charcoal, Industrial Fuel from Controlled Pyrolysis of Sawmill Wastes", The Chemurgic Digest, pp 273-278, August 31, 1946.

134. Article in World Crops, pp 361, September 1957.

135. Tatom, J. W., et al., "A Mobile Pyrolytic System for Conversion of Agricultural and Forestry Wastes into Clean Fuels", Abstract of experiments conducted at Georgia Institute of Technology (1975).

136. Hobsen, P. N., S. Bousfield, and R. Summers, "Anaerobic Digestion of Organic Matter", CRC Critical Reviews in Environmental Control, (June 1974).

137. Livingston, R. S., and McNeill, B., "Beyond Petroleum - A Cost-Benefit and Implementation Comparison of Alternative Non-Petroleum Energy Chains, Volume 1, Biomass Chains", Course Notes, Engineering 235, Stanford University.

138. Stafford. D. A., "Methane Production from Waste", Effluent and Water Treatment Journal, February (1974).

139. "Technology for the Conversion of Solar Energy to Fuel Gas", University of Pennsylvania, January 31 (1974), NTIS, Annual Report.

140. Ghosh, S., and D. L. Klass, "Fuel Gas from Organic Wastes", Chemtech, November (1973).

141. Ghosh, S., and S. L. Klass, "Conversion of Urban refuse to Substitute Natural Gas by the Biogas Process", Proceedings of the Fourth Mineral Utilization Symposium, Chicago, Illinois, May 7-8 (1974).

142. Wise, D. L., E. S. Sadek, and R. G. Kisput", "Fuel Gas Production from Solid Waste", Semi-Annual Progress Report NSF/RANN Contract No. C-827, Dynatech Corporation, Report No. 1151 (1974).

143. Ricci. L. J., "Garbage Routes to Methane", Chemical Engineering, 81(11) (May 27, 1974).

144. Pfeffer, J.T., and J. C. Liebman, "Biological Conversion of Organic Refuse to Methane", Semi-Annual Progress Report NSF/RANN Grant No. GI-39191, Dept. of Civil Engineering, University of Illinois, Urban, Report UILV-ENG-75-2001, 1975.

145. Singh, R. B., "The Bio-Gas Plant-Generating Methane from Organic Wastes", Compost Science, January-February (1972).

146. Bousfield, S., P. N. Hobson, R. Summers, and A. H. Robertson, "Where There's Muck There's Gas", Pig Farming, 79-81 (November 1973).

147. Gaddy, J. L., Park, E. L., Rapp, E. B., "Kinetics and Economics of Anaerobic Digestion of Animal Waste", Water, Air and Soil Pollution, Vol, 3, pp. 161-169 (1974).

148. Spano, L. A., J. Medeiros, and M. Mandels, "Enzymatic Hydrolysis of Cellulosic Wastes to Glucose", U.S. Army Natick Laboratories, Pollution Abatement Division, Food Sciences Laboratory, January 7, 1975.

149. Mandels, M., "Microbial Sources of Cellulase", Cellulose as a Chemical and Energy Resource, C. R. Wilke, editor, John Wiley and Sons, pp 81-105 (1975).

150. Reese, E. T., "Summary Statement on the Enzyme System", Cellulose as a Chemical and Energy Resource, C. R. Wilke, editor, John Wiley and Sons, pp 77-80 (1975).

151. Cowling, C. B., "Physical and Chemical Constraints in the Hydrolysis of Cellulose and Lignocellulosic Materials", Cellulose as a Chemical and Energy Resource, C. R. Wilke, editor, John Wiley and Sons, pp 163-181 (1975).

152. Kirk, T. K., "Lignin - Degrading Enzyme System", Cellulose as a Chemical and Energy Resource, C. R. Wilke, editor, John Wiley and Sons, pp 139-150 (1975).

153. Wilke, C. R., and G. Mitra, "Process Development Studies on the Enzymatic Hydrolysis of Cellulose", Cellulose as a Chemical and Energy Resource, C. R. Wilke, editor, John Wiley and Sons, pp 233-274 (1975).

154. Benemann, J. R., and N. M. Weare, "Hydrogen Evolution by Nitrogen-Fixing Anabaena Cylindrica Cultures", Sciences, 184 (April 12, 1974).

155. Calvin, M., "Solar Energy by Photosynthesis", Science, 184 (April 12, 1974).

156. Mathematical Sciences Northwest, Inc., "Feasibility Study of Conversion of Solid Waste to Methanol or Ammonia", prepared for City of Seattle, September 1974.

157. Duhl, R. W., "Methyl Fuel From Remote Gas Sources", Methanol As An Alternate Fuel, Vol. II, Engineering Foundation Conference, New England College, Henniker, New Hampshire, July 1974.

158. Mathematical Sciences Northwest, Inc., "Feasibility Study of Conversion of Solid Waste to Methanol or Ammonia", prepared for City of Seattle, September 1974.

159. Mathematical Sciences Northwest, Inc., "Feasibility Study of Conversion of Solid Waste to Methanol or Ammonia", prepared for City of Seattle, September 1974.

160. Singh, S., Nack, H., and Oxley, J. H., "Synthesis of Light Hydrocarbon Gases from Coal Gas", paper presented at the Symposium on Coal as a Source of Chemicals, American Chemical Society, New York (April 4-7, 1976).

161. Encyclopedia of Chemical Technology, 2nd Ed., John Wiley and Sons, Inc. Vol 4, pp 446-487 (1964).

162. Bureau of Mines Bituminous Coal Staff, "The Bureau of Mines Synthetic Liquid Fuels Program 1944-1955", Report of Investigation No. 5506 (1959).

163. Rousseau, P. E., "Organic Chemicals and Fischer-Tropsch Synthesis in South Africa", Chemistry and Industry, November 17, 1962, pp 1958-1966.

164. Prescott. J. C., and C. G. Dunn, Industrial Microbiology, 3rd Edition, McGraw-Hill Book Co. (1959) pp. 102-127.

165. Industrial Fermentations, Edited by L. H. Underkofter and R. J. Hickey, Volume 1, Chemical Publishing Co., New York (1954), "Alcoholic Fermentation of Molasses", (H. M. Hodge and F. H. Hldebrandt), pp 73-94.

166. Shreve, R. N., Chemical Process Industries, 34d Edition, McGraw-Hill Book Co., (1967) pp 591-600.

167. Industrial Fermentations, Edited by L. H. Underkofter and R. J. Hickey, Volume 1, Chemical Publishing Co., New York (1954), "The Production of Alcohol from Wood Waste", (J. F. Saeman and A. A. Andreasen) pp 136-171.

168. "They're Packing Up Waste Ponds", Chemical Week, p 37, (June 11, 1975).

169. Griffith, W. L., and A. L. Compere, "New Fixed-Film Process for the Production of High Levels of Ethanol", paper presented at ASM Conference in Energy Production from Organic Wastes and Its Utilization, Madison, Wisconsin, (September 19-21, 1974).

170. Griffith, W. L., and A. L. Compere, "A New Method for Coating Fermentation Tower Packing So As to Facilitate Microorganism Attachment", paper presented at SIM 1975 Annual Meeting, University of Rhode Island, Kingston, Rhode Island, (August 17-22, 1975).

171. Compere, A. L., and W. L. Griffith, "Fermentation of Waste Materials to Produce Industrial Intermediates", paper presented at SIM 1975 Annual Meeting, University of Rhode Island, Kingston, Rhode Island (August 17-22, 1975).

172. Compere, A. L., and W. L. Griffith, "Determination of the Coefficient of Decay for a Mixed Culture of Methane Producing Organisms", paper presented at ASM Conference on Energy Production from Organic Wastes and Its Utilization, Madison, Wisconsin, (September 19-21, 1974).

173. Shreve, R. N., Chemical Process Industries, 3rd Edition, McGraw-Hill Publishing Co. (1967) "Fermentation Industries", pp. 608-610.

174. Industrial Fermentation, edited by L. A. Underkofler and R. J. Hickey, Vol. 1, Chemical Publishing Co., New York, (1954), "The Butanol-Acetone Fermentations" (W. N. McCutchan and R. J. Hickey), pp. 347-387.

175. Prescott, S. C., and C. G. Dunn, Industrial Microbiology, 3rd Edition, McGraw-Hill Publishing Co. (1959), "The Acetone-Butanol Fermentation", pp. 250-284.

176. Prescott, S. C., and Dunn, C. G., Industrial Microbiology, 3rd Edition, McGraw-Hill Publishing Co. (1959), Chapter 1 , pp. 285-294.

177. Meisel, S. L., J. P. McCullough, C. H. Lechthaler, P. B. Weisz, "Gasoline from Methanol in One Step", Chem Tech. (February 1976).

178. Perry, R. H. and C. H. Chilton, Chemical Engineers' Handbook, 5th Edition, McGraw-Hill Book Company, New York, Chapters 6 and 7 (1973).

179. Manual of Pipeline Construction, Pipe Line Contractors Association, Paris (1972).

180. Fetherston, F. R., Handbook of Compressed Gases, Compressed Gas Association, Incorporated, Reinhold Publishing, New York (1966),

181. Ballantyne, W. E., Singh, S., and DiNovo, S. T., "Preliminary Environmental Assessment of the Production and Use of Methanol From Non-Coal Sources", draft of Final Report from Battelle's Columbus Laboratories to U.S. Environmental Protection Agency, June 22, 1976.

182. Hall, F. H., et al., "Comparison of Fossil and Wood Fuels", Final report from Battelle's Columbus Laboratories to the Environmental Protection Agency. Contract No. 68-02-1323, March, 1976. [Report No. EPA-600/2-76-056]

183. Agricultural Stabilization and Conservation Service. 1974. Annual Report. USDA, ASCS, Alexandria, Louisiana. 66 p.

184. Burr, G. O., C. E. Hart, H. W. Brodie, T. Tanimats, H. P. Takahashi, F. M. Ashton, and R. E. Coburn. 1957. The sugarcane plant. Ann. Rev. Plant Physiol. 8:275-308.

185. Statistical Abstract of the United States, Data from 1970 Census (1975).

186. Baez, L., Personnel Communication, Bureau of Sanitation, City of Los Angeles.

187. Telephone communication between Mr. P. C. Woodruff of the Ohio Division of Natural Resources and Wayne Ballantyne of Battelle's Columbus Laboratories, July 9, 1976.

188. Huang, C. J., "Energy Recovery from Solid Waste - Volume 2", prepared for Lyndon B. Johnson Space Center, NASA, April, 1975.

189. Finney, C. S., and Garrett, D. E., "The Flash Pyrolysis of Solid Wastes", Energy Sources, Volume 1 (3), Crane, Russak & Company Publishers (1974).

190. Telephone communication between Stan Bozdech of DeKalb Company and Wayne Ballantyne of Battelle's Columbus Laboratories, April 30, 1976.

191. Grantham, J. B., and Ellis, T. H., 1974, Potentials of Wood for Producing Energy, J. Forestry 72:552.

192. Leaf, A. L., Davey, C. B., and Voigt, G. K., 1971. Forest Soil Organic Matter and Nutrient Element Dynamics in D. L. Dindal, Ed. Proc. of the First Soil Microcommunities Conference, Syracuse, N.Y., U.S. Atomic Energy Commission, Office of Information Services.

193. Gosz, J. R., Likens, G. E., and Bormann, F. H., 1973, Nutrient Release from Decomposing Leaf and Branch Litter in the Hubbard Brook Forest, New Hampshire, Ecol. Monogr. 43(2):173.

194. Ovington, J. D., Heitkamp, D., and Lawrence, D. B., 1963, Plant Biomass and Productivity of Prairie, Savanna, Oakwood, and Maize Field Ecosystems in Central Minnesota. Ecol. 44(1):52.

195. Chapell, T. W., and Beltz, R. C., 1973, Southern Logging Residues: An Opportunity, J. Forestry 71:688.

196. State of Vermont, Governor's Task Force on Wood as a Source of Energy, Samuel Lloyd, Acn. 1975.

197. McVicker, J. S., 1942, The Influence of Soil Type on the Composition and Yield of White Oak Leaves, Abstracts of Ph.D Thesis, Univ. of Illinois, Urbana, Ill. in Kittredge, J. Forest Influences: The Effects of Woody Vegetation on Climate, Water, and Soil, Dover Publ. Inc., New York (1948).

198. Kittredge, J., 1948. See Ref. 4 for complete citation.

199. Johnson, W. M., 19740, Infiltration Capacity of Forest Soil as Influenced by Litter. J. Forestry 38:520.

200. Linsley, R. K., and Franzini, J. B., 1972, Water Resources Engineering, McGraw-Hill, Inc. New York.

201. Bormann, F. H., Likens, G. E., Siccama, T. G., Pierce, R. S., and Eaton, J. S., 1974, The Export of Nutrients and Recovery of Stable Conditions Following Deforestation at Hubbard Brook, Ecol. Monogr. 44(3): 255.

202. Montgomery Consulting Engineers, Inc., 1976, Forest Harvest, Residue Treatment, Reforestation and Protection of Water Quality. Report to U.S.E.P.A. Region X EPA 910/9-76-020.

203. Wooldridge, D. D., 1970, Chemical and Physical Properties of Forest Litter Layers in Central Washington in Montgomery Consulting Engrs. See Ref. 12 for citation.

204. Wischmeier, W. H., and Smith, D. D., 1959, A Rainfall Erosion Index for a Universal Soil Loss Equation. Proc. of the Soil Scien. Soc. of Amer. 23(3):246.

205. Wischmeier, W. H., and Smith, D. D., 1965,Predicting Rainfall - Erosion Losses from Cropland East of the Rocky Mountains in EPA, 1972. See Ref. 208 for citation.

206. Wischmeier, W. H., 1972, Estimating the Cover and Management Factor for Undisturbed Areas in Methods for Identifying and Evaluating the Nature and Extent of Non-Point Sources of Pollutants. EPA 430/9-73-014.

207. Dyrness, C. T., 1966, Erodibility and Erosion Potential of Forest Watersheds in EPA, 1973. See Ref. 14 for citation.

208. Marks, P. L., and Bormann, F. H., 1972. Revegetation Following Forest Cutting: Mechanisms for Return to Steady-State Nutrient Cycling, Science 176:914.

209. Toumey, J. W., and Neethling, E. J., 1924. Insolation, A Factor in the Natural Regeneration of Certain Conifers, Yale Univ. School of Forestry Bull. 11 in Kittredge. See Ref. 4 for citation.

210. Bates, C. G., and Henry, A. J., 1928, Forest and Streamflow at Wagon Wheel Gap, Colorado in Kittredge, J., see Ref. 4 for complete citation.

211. Reichle, D. E., 1971, Energy and Nutrient Metabolism of Soil and Litter Invertebrates. Symposium on the Productivity of Forest Ecosystems of the World. Polais des Congres, Bussels, Belgium.

212. Jemison, G. M., and Lowden, M. S., 1974, Management and Research Implications in Environmental Effects of Forest Residues Management in the Pacific Northwest, a State of Knowledge Compendium, USDA Forest Serv. Gen Tech. Report DNW-24 Pacific Northwest Forest and Range Expt. Stat. Portland, OR.

213. Keeney, D. R., Lee, K. W., and Walsh, L. M., 1975, Agriculture Crop Residue/Energy Crops Guidelines for the Application of Waste Water Sludge to Agricultural Land in Wisconsin. Tech. Bulletin 88. Department of Natural Resources, Madison, Wisconsin.

214. Gerloff, G. C., 1976, Unpublished course notes, University of Wisconsin-Madison.

215. USDA, 1971, Mulch Tillage in Modern Framing. Leaflet No. 554.

216. Agricultural Research Service - USDA, 1975, Control of Water Pollution from Cropland, Vol. 1, A Manual for Guideline Development, EPA 600/2-75-026a.

217. Hensler, R. F., Erhardt, W. H., and Walsh, L. M., 1971, Effect of Manure Handling Systems on Plant Nutrient Cycling in Livestock Waste Management and Pollution Abatement Proc. International Symp. on Livestock Wastes, Ohio State University.

218. Loehr, R. C., 1974, Agricultural Waste Management: Problems, Processes, and Approaches. Academic Press, New York.

219. Taiganaides, E. P., White, R. K., and Strashine, R. L., 1971, Water and Soil Oxygen Demand of Livestock Wastes in Livestock Waste Management Proc. See Ref. 217 for citation.

220. Fair, G. M., Geyer, J. C., and Okun, D. A., 1968, Water and Waste Water Engineering, Vol 2. John Wiley and Sons, Inc., New York.

221. Tamplin, A. R., 1973, Solar Energy: How Shall We Use The Sunlight? Let us Count the Ways. Environment 15(5):16.

222. Nordstedt, R. A., and Taiganides, E. P., 1971, Meteorological Control of Malodors from Land Spreading of Livestock Wastes *in* Livestock Waste Management Proc. See Ref.217 for citation.

223. Miner, J. R. 1974. Odors from Confined Livestock Production: A State of the Art. EPA 660/2-74-023.

224. Ludington, D. C., and Sobel, A. T., 1970, Moisture Increased Manure Odors. Poultry Digest, p 445.

225. Hileman, L. H., 1971. Effect of Rate of Poultry Manure Application Selected Soil Chemical Properties *in* Livestock Waste Management Proc. See Ref.217 for citation.

226. Szetela, E. J., Krascella, N. L., and Blecher, W. A., 1974. Technology for Conversion of Solar Energy to Fuel, Mariculture Investigation: Ocean Farming and Fuel Production, United Aircraft Research Labs. N911599-4.

227. Mann, K. H., 1973, Seaweeds: Their Productivity and Strategy for Growth. Science 182(416):975.

228. Khailov, K. M., and Burlakova, Z.P. 1969, Release of Dissolved Organic Matter by Marine Seaweeds and Distribution of Their Total Organic Production to Inshore Communities. Limnol. and Oceanogr. 14(4):521.

229. Provasoli, L., 1963., Organic Regulation of Phytoplankton Fertility *in* M. N. Hill, ed. The Sea, John Willey - Interscience, New York.

230. Stephens, G., 1967, Dissolved Organic Material as a Nutritional Source For Marine and Estuarine Invertebrates *in* G. H. Lauff, ed. Estuaries. AAAS, Publ. No. 83 Washington, D.C.

231. Battelle Columbus Laboratories and Battelle Pacific Northwest Laboratories, 1973, Environmental Considerations in Future Energy Growth. Report to the Office of Research and Development, Environmental Protection Agency.

232. Odum, E. P., 1971, Fundamentals of Ecology. W. B. Saunders Co., Philadelphia 3rd Ed.

233. Buttery, B. R., and Lambert, J. M., 1965, Competition Between *Glyceria maxima* and *Phragmites communes* in the Region of Surlingham Broad. J. Ecol. 52:163.

234. Willingham, C. A., Engstrom, D. G., Cornaby, B. W., and Crowner, A.E., 1974, A Study of Coastal Zone Ecosystems in the Gulf of Mexico in Relation to Gas Pipelining Activities, Interim Report, Battelle Columbus Laboratories.

235. Pomeroy, L. R., 1959, Algae Productivity in the Salt Marshes of Georgia, Limnol and Oceanog, 4:386.

236. Albrecht, W. A., 1942, Soil Organic Matter and Ion Availability for Plants, Soil Science: 487.

237. Gorham, E., 195 , Chemical Studies on the Soils and Vegetation of Waterlogged Habitats in the English Lake District, J. Ecol. 41:345.

238. National Center for Resource Recovery, Inc., 1973, Municipal Solid Waste Collection, A State of the Art Study, Lexington Books, D. C., Health and Co., Lexington, Mass.

239. Carnes. R. A. 1976, Analyzing Sanitary Landfill Leachate. News of Environmental Research in Cincinnati, Municipal Environmental Research Laboratory.

240. Mays, D. A., Terman, G. L., and Duggan, J. C., 1973, Municipal Compost: Effects on Crop Yields and Soil Properties, J. Environ. Quality 2(1):89.

241. Hughes, E. E., Dickson, E. M., and Schmidt, R. A., 1974, Control of Environmental Impacts from Advanced Energy Sources, EPA-600/2-74-002.

242. Surprenant, N., Hall, R., Young, C., Durocher, D., Slater, S., Susa, T., Sussman, M., 1976, Preliminary Emissions Assessment of Conventional Stationary Combustion Systems, Final Report by GCA Corporation to U.S. EPA-R.T.P., Appendix I to Exhibit A, Vol. II.

243. U.S. EPA, 1975, San Diego County Demonstrates Pyrolysis of Solid Waste, Report on Work Performed Under Federal Solid Waste Management Demonstration Grant No. S-801588.

244. Bennington, G., McGurk, B., Salo, G., Spewak, P. and Wan, E., 1976, Preliminary Considerations for an Evaluation of Silviculture Energy Plantations, Working Paper presented by MITRE Corp. to ERDA/DSE.

245. McIntyre, A. D. and Papic, M. M., 1974, Pyrolysis of Municipal Solid Waste, Can. J. of Chem. Engineering, 52:263.

246. Finney, C. S., and Garrett, D. E., 1974, The Flash Pyrolysis of Solid Wastes, Energy Sources 1(3):295, Crane, Russak, and Co., Publ.

247. Garner, W., Bricker, C. E., Ferguson, T. L., Wiegand, C.J.W., and McElroy, 1971. Pyrolysis as a Method of Disposal of Cattle Feedlot Wastes, Midwest Research Institute Report to EPA under Contract 14-12-850.

248. Ghosh, S. and Klass, D. L., 1974, Conversion of Urban Refuse to SNG by the Biogas Process, Proc. of the Fourth Mineral Utilization Symposium.

249. Huang, C. J., et al., 1975. Energy Recovery from Solid Waste. Volume 2 Technical Report, NASA Washington, D.C.

250. McCartey, P., "Anaerobic Waste Treatment Fundamentals: Part III - Toxic Materials and Their Control", Public Works, pp. 91-94 (November 1964).

251. Malina, J. F., "Anaerobic Waste Treatment", Process Design in Water Engineering, University of Texas (1967).

252. Kugelman, I. J., and Chin, U. K., Ed. by Pohland, F. G., "Toxicity, Synergism and Antagonism in Anaerobic Waste Treatment Processes", Conference on Anaerobic Biological Treatment Processes, Advances in Chemistry, Series 105, American Chemical Society, Washington, D.C., pp. 55-91 (1971).

253. Ghosh, S. and Klass, D. L., 1976, SNG from Refuse and Sewage Study by the Biogas Process, Symposium Papers on Clean Fuels from Biomass, Sewage, Urban Refuse, and Agricultural Wastes, Institute of Gas Technology.

254. Douglas, R. W., 1976, Synthetic Natural Gas from Animal Waste by Anaerobic Fermentation, Symposium Papers on Clean Fuels from Biomass, Sewage, Urban Refuse, and Agricultural Wastes, Institute of Gas Technology.

255. Harris, E. E., 1949. Wood Saccharification in Advances in Carbohydrate Chemistry. Volume 4 Academic Press, New York.

256. Converse, A. O., Grethlein, H. E., Karandikar, S., and Kuhrtz, 1973. Acid Hydrolysis of Cellulose in Refuse to Sugar and its Fermentation to Alcohol. EPA 670/2-73-11.

257. Huffman, G. L., "Processes for the Conversion of Solid Wastes and Biomass Fuels to Clean Energy Forms," A Conference on Capturing the Sun Through Bioconversion, March 10-12, 1976, Washington, D. C., pp 454-484.

258. Solid Waste Demonstration Projects, Proceedings of a Symposium, Cincinnati, May 4-6, 1971, U.S. Environmental Protection Agency, publication (SW-4p).

259. Solid Waste Recycling Project, A National Directory, Publication SW-45, U.S. Environmental Protection Agency (1973).

260. Definition Report: National Solar Energy Research, Development, and Demonstration Program. Solar Energy Division of ERDA. June, 1975.

261. Ward, R. F., 1976. Federal Fuels from Biomass Energy Program, Clean Fuels from Biomass, Sewage, Urban Refuse, and Agricultural Wastes, Orlando, Florida (January 26-30, 1976).